BITUMINOUS MIX DESIGN FOR HOT CENTRAL PLANT RECYCLING

A Thesis Submitted

In Partial Fulfilment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

by

ARAVIND K

to the

Department Of Civil Engineering

Indian Institute of Technology Kanpur

June, 2005

Certificate

It is certified that the work contained in the thesis entitled **BITUMINOUS MIX DESIGN FOR HOT CENTRAL PLANT RECYCLING**, by Aravind K has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

Animesh Das

(**Dr. Animesh Das**)

Assistant Professor

Department of Civil Engineering

I. I. T. Kanpur

20th June, 2005

SYNOPSIS

Hot mix recycling is one of the techniques commonly adopted for recycling of bituminous pavement due to its inherent advantages. An attempt has been made in this work to improve the existing mix design methodology where material quantity is not prefixed. Linear programming has been used in formulation of this new methodology. The formulation can take care of objectives like cost minimization, material usage maximization etc. Performance based tests like fatigue tests and creep tests have been done for validation of proposed methodology.

Acknowledgements

I am deeply indebted to Dr. Animesh Das, my thesis supervisor, for his instructions and guidance throughout the thesis work. I am particularly thankful to him for his friendly advise throughout degree program and introducing me into field of pavement engineering.

I am also thankful to Dr. Partha Chakroborty and Dr. B. R. Marwah for giving me insight into field of Transportation Engineering.

Also I am thankful to Transportation Engineering laboratory staff Mr. Pankaj Gupta and Mr. Manoj for their help during the fabrication of creep testing setup and lab work. Thanks to Dr. K. K. Bajpai and Mr. Kamlesh for their help in writing LabView program. A very special thanks to Mr. Sant Kumar for his sincere work, without which I could not have completed my experiments in time.

Thanks to my transportation group members Ujjal, Amit, Neeraja, Ranja, Akhilesh and Durgesh for their support and cooperation during laboratory work.

Last but not the least I would also like to thank my parents and brother Aditya for their constant support which brought me till here.

Aravind K

Dedicated

To

My Parents

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Chapter 1

Introduction

1.1 Introduction

Large amount of construction materials are needed for highway construction and its maintenance. At the same time old materials are being replaced with new materials during reconstruction. However this has put undue pressure on nature, leading to wastage of natural resources and energy disposal problem.

Thus, effort is being put to reduce the use of virgin materials in highway construction. One of the available options is to reuse old materials of existing pavement i.e. recycling of pavement materials.

In advanced countries, asphalt is the most recycled material in construction industry. For example, in USA, 33 million tons of Reclaimed Asphalt Pavement (RAP) is used per year for recycling purpose which is around 80% of the total amount of RAP collected from old asphalt pavements [12]. The amount of RAP used for recycling per year is about 0.84 million tons in Sweden, 7.3 million tons in Germany, 0.53 million tons in Denmark and 0.12 million tons in Netherlands [12]. In the year 1995, 20 million tons of recycled hot mix was produced in Japan, which constituted 30% of the total hot mix production [13]. However bituminous pavement recycling is not yet a very popular

method in India.

Some of the advantages associated with recycling of pavement materials are as follows:

1. Less user delay
2. Conservation of energy [27]
3. Preservation of environment
4. Reduced cost of construction [5, 27, 34]
5. Conservation of aggregate and binders [34]
6. Preservation of existing pavement geometrics [1]
7. Reducing demand for land-fill areas [3].

1.2 Objective

Design of recycled mix involves determining the proportions of components like RAP, new aggregate and fresh bitumen. The objective of this thesis can be as identified as follows:

1. Development of formulation of constituent proportioning of recycled mix.
2. Validation of the proposed mix composition by conducting performance related tests.

1.3 Organization

This thesis contains six chapters of which this is the first one. This chapter is followed by literature review, where a review of topics related to bituminous pavement

recycling is presented. Chapter 3 presents the proposed method for recycling the old bituminous material. The Chapter 4 is on experimental studies; this chapter explains the experiments carried out on mixes prepared using mix design proposed in Chapter 3. Chapter 5 discusses the findings of experimental investigation. The conclusions and further scope have been given in Chapter 6. Finally the appendices at the end of thesis give the notations used in present study and the raw data of experimental investigations.

Flow chart explaining sequence of work has been presented in Figure 1.1.

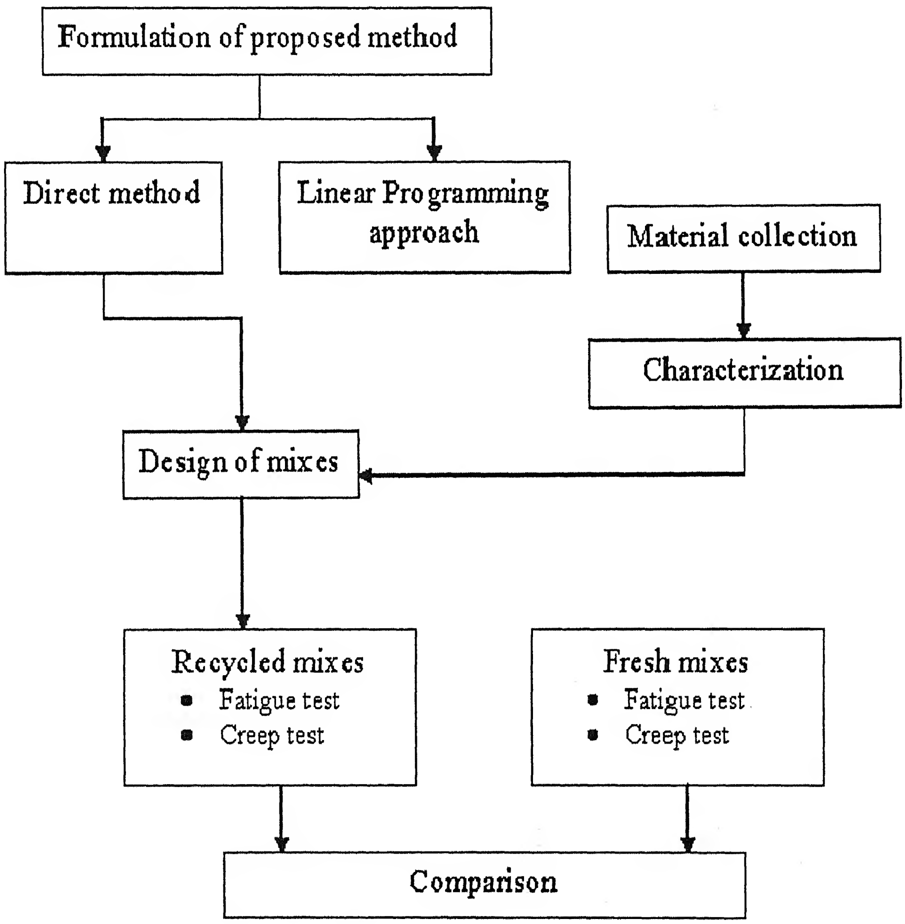

Figure 1.1: Flow chart explaining the sequence of work

Chapter 2

Background and Literature Review

2.1 Introduction

This chapter discusses briefly the background related to recycling of bituminous pavement. The various topics that are discussed in this chapter are bitumen chemistry, physical characterization of bitumen, ageing of bitumen, recycled mix design and recycling methods. These topics are discussed as individual sections in the following.

2.2 Bitumen Chemistry

2.2.1 Origin and composition of bitumen

Bitumen, a complex hydrocarbon, is derived from fractional distillation of crude petroleum. Depending on the source and method of distillation, the constituents of bitumen vary considerably. Chief elements in bitumen are carbon, hydrogen, sulfur. Also nitrogen and oxygen are present in small amounts, which play important role in physical properties of bitumen like boiling point, viscosity etc. Sometimes metals like vanadium, iron and nickel are also present in bitumen [10, 9]. Table 2.1 presents elementary

constituents of bitumen.

Table 2.1: Elementary constituents of bitumen [28]

	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen (%)	Nickel (ppm)
Range	80.2-84.3	9.8-10.8	0.2-1.2	0.9-6.6	0.4-1.0	10-139
	Iron (ppm)	**Manganese (ppm)**	**Calcium (ppm)**	**Magnesium (ppm)**	**Sodium (ppm)**	**Vanadium (ppm)**
Range	5-147	0.1-3.7	1-135	1-134	6-159	7-1590

2.2.2 Molecular structure

The molecular weight of unaged bitumen is of the range of 300-2000 [9]. However, as a result of molecular association, bitumen behaves as if it had a larger molecular weight [9]. Depending on source of bitumen the molecular structure varies.

Due to extremely large number of molecules and chemical structure in bitumen, attempts have been made to separate bitumen into generic fractions based on size and polarity [10]. Some times this may be based on solubility and absorption [9].

Depending on solubility in chemicals its constituents are classified into various functional groups. For example, based on solubility in n-heptane, bitumen is divided into asphaltenes and maltenes. Asphaltenes are the complex group of molecules, which precipitate when bitumen is dissolved in pentane. Due to their high polarity, the asphaltene fraction tend to interact more. Maltenes, soluble fraction of bitumen in pentane act as dispersing phase for asphlatenes. Maltenes are further divided into saturates, aromatics and resins. Aromatics can be of two types: naphthene aromatics and polar aromatics [14]. Among these fractions, asphaltenes and resins have higher molecular weight where as aromatics and saturates have lowest molecular weight. The classification system is presented schematically in Figure 2.1.

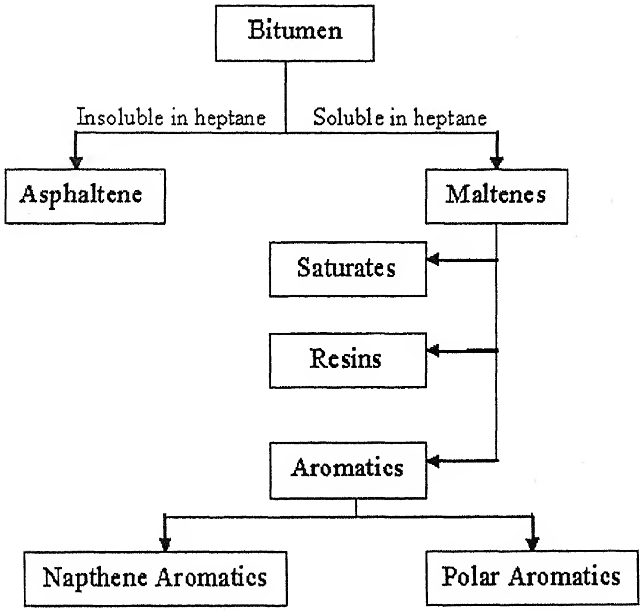

Figure 2.1: Bitumen classification based on solubility in heptane

This type of characterization also depends upon solution temperature [9] and nature of solvent. Typical structures of asphaltene, saturates and aromatic are given in Figure 2.2, Figure 2.3 and Figure 2.4 respectively.

2.3 Physical Characterization

Traditionally for engineering purpose bitumen is classified based on physical characteristics. Some of the physical characteristics based on which classification are done are softness, flow characteristics, adhesion with surfaces etc.

The penetration test gives some idea about consistency of the bitumen. The cohesion can be estimated by performing ductility test on the bitumen samples. Its degree of softness can be characterized by softening point test. Even though these tests are empirical in nature they aid in estimation of engineering properties of bitumen.

It may be noted that the above tests are single point tests i.e. properties are measured

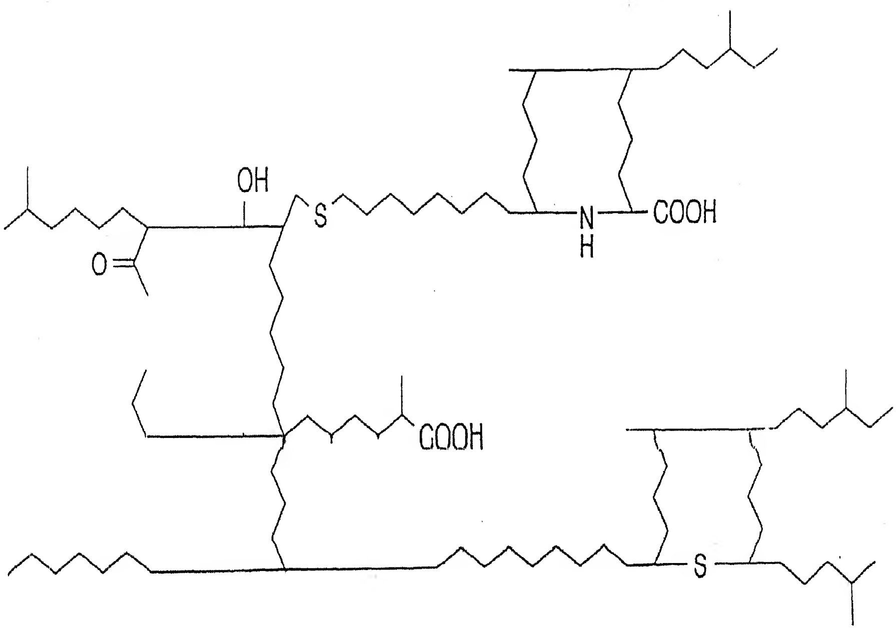

Figure 2.2: Schematic structure of asphaltenes [28]

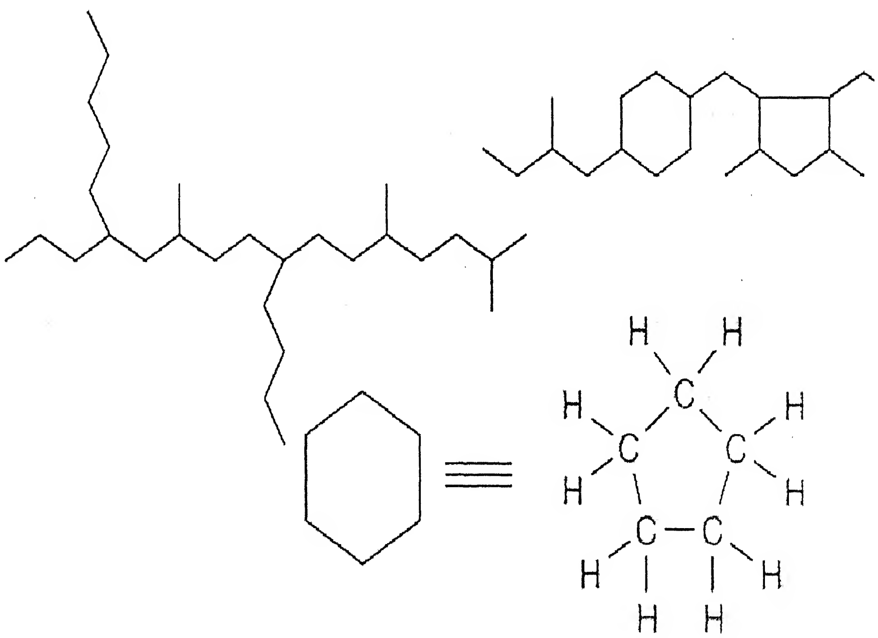

Figure 2.3: Schematic diagram of saturates [28]

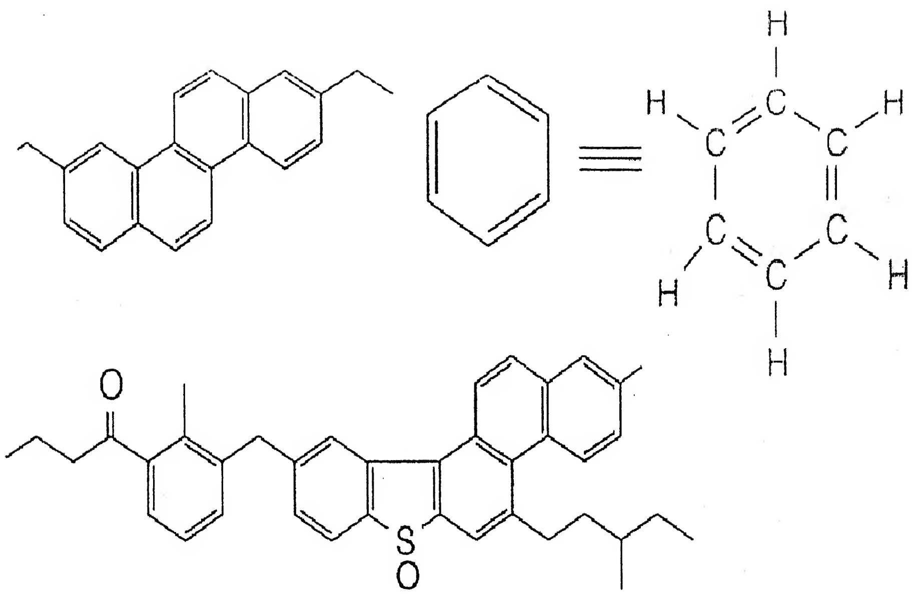

Figure 2.4: Schematic diagram of aromatic structures [28]

at single temperature. However, since the bitumen and mix has to perform well over a range of temperature, test procedures adopted should be such that it can cover a range of temperature in which bitumen mix is supposed to serve satisfactorily. At higher temperature or longer time of loading bitumen acts as viscous liquid where as at low temperature or shorter loading time bitumen acts as an elastic solid. However at intermediate service condition temperature, bitumen acts as visco-elastic material [28]. Viscosity an indicator of flow can be measured easily at different temperatures. Traditionally viscosity has been measured by different tests like Brookfield viscometer, Rotational viscometer etc.

2.3.1 Effect of constituents on physical characterization

Amount of asphaltenes plays an important role in bitumen viscosity. Asphaltenes, being polar in nature, tends to associate among themselves, forming big sized molecules. However aromatics and resin fraction keeps asphaltene in dispersed phase (peptizing

ability). That is if resin and aromatic component percentage is less, then the bitumen becomes more viscous [28, 10], with non-Newtonian behavior. With increase in sulfur content the specific gravity is observed to be increasing [32]. As aromatic compounds increase and saturated compound decrease the density of bitumen is found to increase.

2.3.2 Closing remarks

It has been observed that in spite of composition remaining same, there is variation in physical characteristics of bitumen [9]. Figure 2.5 shows such an example. Also, there are some examples where similar performing (similar physical properties) bitumen have different chemical composition [9].

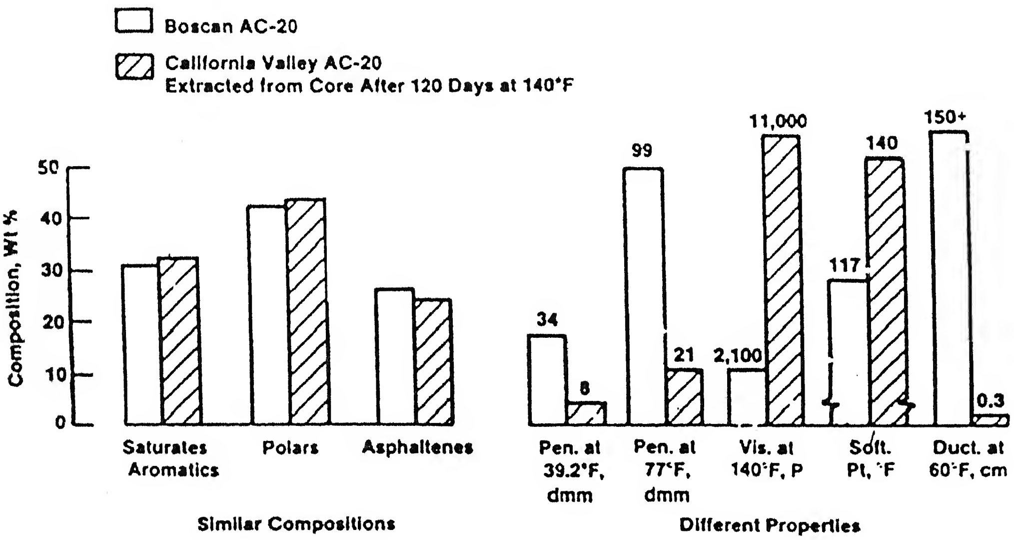

Figure 2.5: Asphalt with similar composition but different property [9]

As per the present understanding, a definite relationship could not be obtained between the bitumen chemistry to its field performance. A number of researchers [9, 14] have commented that there is in fact no significant relation with the chemistry of bitumen to the engineering behavior of bitumen as a material.

2.4 Ageing of Bitumen and Ageing Indices

Ageing is a phenomenon during which properties/composition of the bitumen changes. Some of the changes taking place during this process are [3, 10]:

1. Loss of oily / volatile compounds while heating,
2. Change in chemical composition from reaction with atmospheric oxygen,
3. Molecular restructuring (polymerization)/Steric hardening.

Volatile loss causes reduction in weight of bitumen, whereas oxidation causes increase in weight. Thus, the final change in weight will be governed by whichever phenomenon dominates for a particular bitumen. For same grade of bitumen, ductility of fresh bitumen is often more as compared to aged bitumen. This is due to fact that bitumen harden with ageing. Similar trend is observed in case of penetration also. Figure 2.6 and Figure 2.7 show variation of penetration with field and laboratory ageing conditions collected from literature. During the ageing process, molecular restructuring, crystallization takes place. These changes in turn lead to increasing viscosity and softening point with aging. Increase in softening point and dynamic viscosity with time is shown in Figure 2.8 and 2.9 respectively.

During heating and mixing of bitumen with hot aggregates, changes are observed in certain properties of bitumen, which is known as short term ageing. While heating bitumen, volatiles having low boiling point (primarily non-polar hydrocarbons [26]) gets evaporated. Further changes occurring is dependent on duration of storage of hot bitumen at elevated temperature. Rolling Thin Film Oven Test (RTFOT) is useful in simulating short term ageing [18] under laboratory scale.

Under the action of environment and vehicular traffic, changes taking place in bituminous layer are referred as long term ageing. Studies conducted have indicated that bitumen is more susceptible to changes in viscosity when exposed to higher temperature due to oxidation [18].

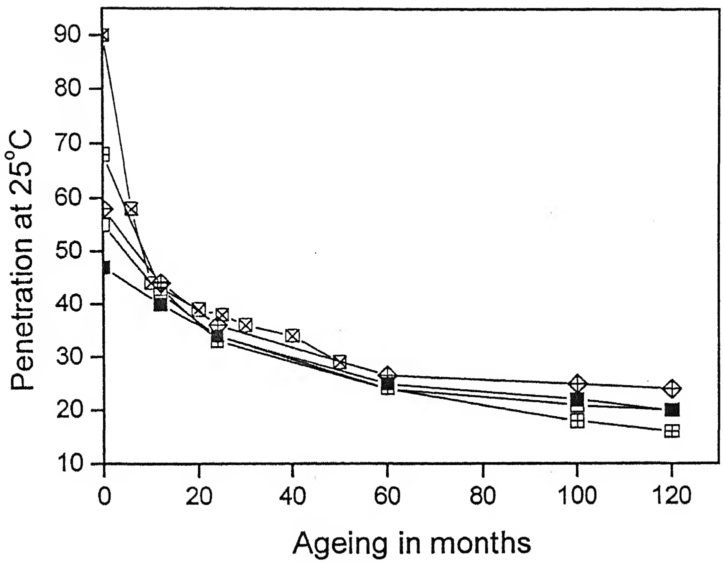

Figure 2.6: Variation of penetration with field ageing [16, 21]

It has been reported that ageing of bituminous mix is influenced by time, temperature, asphalt content, voids, aggregate porosity, presence of trace metals, asphalt thickness [9, 10]. With the presence of more voids, sufficient space is available for air circulation. This in turn exposes the bitumen coating to atmospheric changes. Hence it can be said that increase in voids content in the mix leads to increased ageing of bitumen [18].

It is found that during mixing asphaltene content increases while saturates remain constant. The saturates remain constant because of their inert nature [14]. On the other hand under service condition asphaltene percentage increases, polar aromatics and naphthene aromatics fraction decreases.

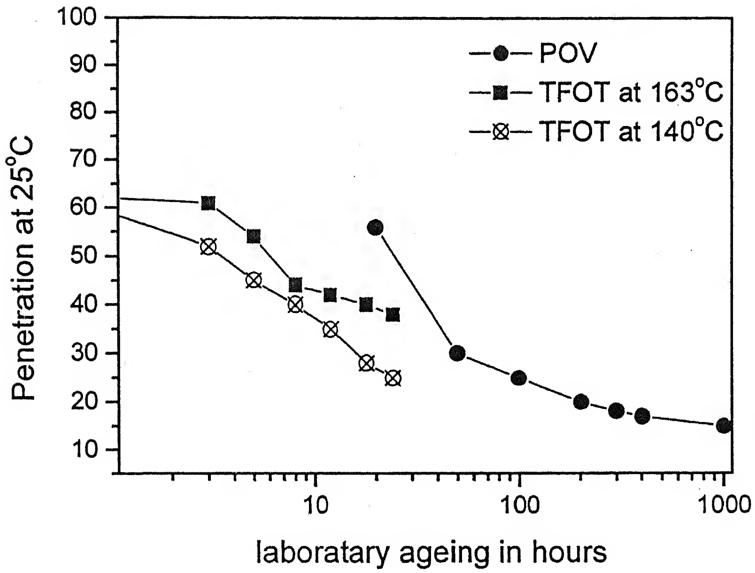

Figure 2.7: Variation of penetration with laboratory ageing [14, 21]

2.5 Recycling Methods

2.5.1 Classification

Based on the process adopted in recycling the bituminous mix, it can be broadly classified as central plant recycling and in-situ recycling. If the RAP is modified at a plant, away from construction site then the process is known as central plant recycling. In in-situ recycling process the RAP modified in place, where from it is available. Further, the RAP could be heated to condition it. If heat is applied then the process is known as hot mix recycling. In case of cold mix recycling, old materials are conditioned using recycling agent (like, low viscosity emulsion) without application of heat. The classification system is presented schematically in Figure 2.10.

Another way of classification could be based on the depth of the old pavement removed [7]. If the top layers of pavement fail, then the upper layers are removed and laid again. This process is known as surface recycling. However, if base failure occurs

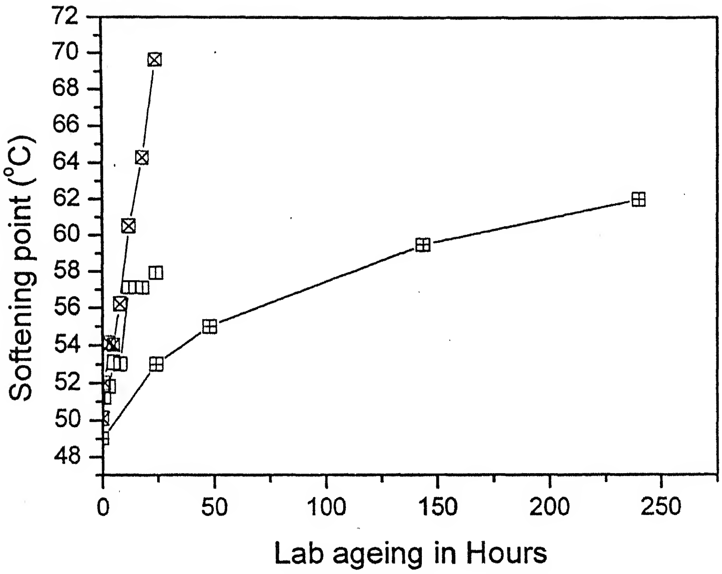

Figure 2.8: Variation of softening point temperature with laboratory ageing

then the pavement layers up to base layer is removed and constructed again. This process is known as full depth reclamation. The following paragraphs elaborate further the various recycling processes based on the classification scheme presented in Figure 2.10.

2.5.2 Hot in-place recycling

Initially the pavement intended to be recycled is heated to a higher temperature using suitable heating arrangement. This facilitates easier removal of materials. After heating, the pavement surface is scarified to the required depth. Further, depending on the requirement new aggregate and binder are added. The material is mixed well and compacted to the required thickness. As this process consumes less time, least disruption to traffic is caused. Also the transportation cost is less, as materials need not be taken away. Machinery required for this purpose being bulky in nature, sufficient right-of-way is required. This becomes an important consideration for in-place recycling within the city areas [15].

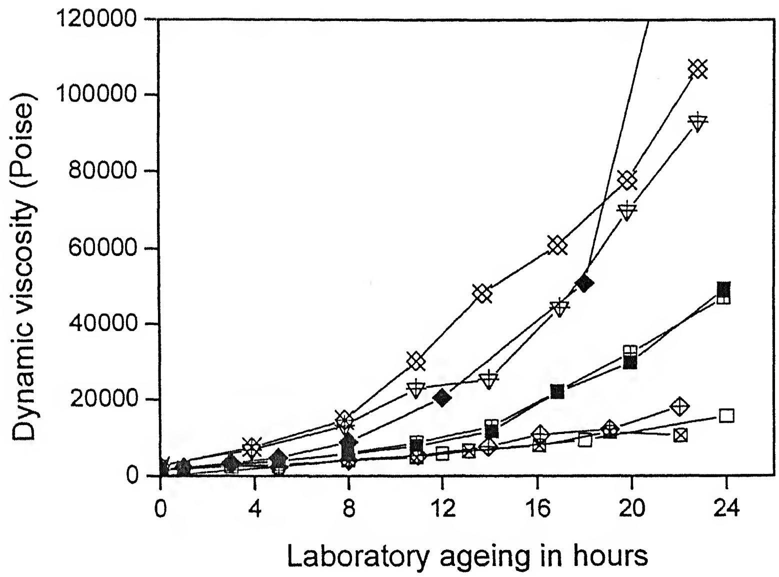

Figure 2.9: Variation of dynamic viscosity with laboratory ageing [14, 33]

2.5.3 Cold in place recycling

In cold in-place recycling process, first, the pavement is scarified with a scarifier. The scarified material is crushed to the required gradation. Then the required amount of new aggregates and binder in cold form (emulsion or cutback) is added. It is compacted and left for aeration. During this process additives like, cement, quick lime, fly ash may be used. The cold mix recycling takes care of local geometric correction, correction of pavement distresses like surface cracks [24]. Being an in-situ process the hauling cost is considerably low. Since the old pavement materials are not heated, emission of smoke is less. Hence air quality related problems during construction is less as compared to hot mix process [22]. Similar to hot in place recycling process the machinery required being bulky, sufficient maneuvering space should be available for operating the equipment. Also, the lane needs to be closed for certain time so that sufficient time is available for curing of freshly laid course. Moisture content (when bitumen emulsion is used) needs to be given importance as it influences gradation control, mixing and workability of recycled mix to a large extent [24].

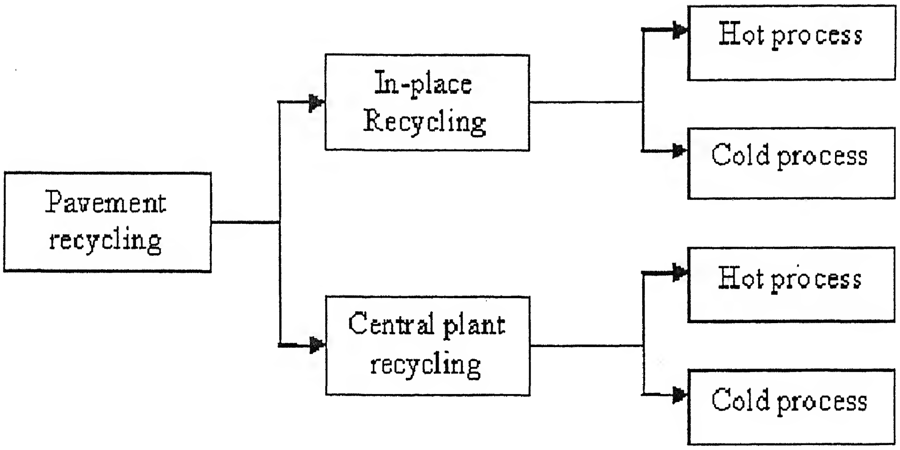

Figure 2.10: Classification of recycling methods based on processes

2.5.4 Hot central plant recycling

In this process, RAP is combined with required quantity of bituminous binder, and new aggregates in a hot mix plant. The resultant mix is heated to an elevated temperature and mixed thoroughly. The hot mix is transported to paving site, placed, and compacted to the required compaction level. The main advantage of this process is that the mix properties and performance is comparable to that of virgin mix [34]. Epps et al. [7] have noted that the quality control in this process is better when compared to hot in-place recycling. As RAP is susceptible to moisture, care needs to be taken while storing it. Less workspace is required for laying the recycled mix, hence this is suitable for the roads where the right-of-way is somewhat restricted. The RAP should not be exposed to extremely high temperature as it causes pollution due to smoke emission [5, 34].

2.5.5 Cold central plant recycling

This is the similar process as is the hot central plant mixing, except it does not involve any heating, and therefore emulsion bitumen is used binder in most of the cases. Precise control on the mixing time is important, over-mixing may cause premature breaking

of emulsified bitumen, under-mixing results in insufficient coating of aggregates.

2.6 Mix Design

This section reviews the principles adopted in various recycled mix design guidelines.

2.6.1 Asphalt Institute procedure

As per the Asphalt Institute procedure [2, 23], the approximate demand of bitumen of the recycled mix is estimated by using an empirical formula. This empirical formula is based on the concept of minimum film thickness required to cover the total surface area of the aggregates. The total surface area of the aggregates can be obtained empirically from the aggregate gradation, or can be estimated through Centrifuge Kerosene Equivalent (CKE) test.formula given by Asphalt Institute [23] has been given below.

$$P = .035a + .045b + Kc + F \tag{2.1}$$

where P = approximate total bitumen demand of recycled mix, percent by weight of mix, a = percent of mineral aggregate retained on 2.36mm sieve, b = percent of mineral aggregate passing on 2.36mm sieve and retained on 75μ sieve, c = percent of mineral aggregate passing 75μ sieve, K = .15 for 11 - 15 percent passing 75μ sieve,.18 for 6 - 10 percent passing 75μ sieve, .2 for 5 percent or less passing 75μ sieve, F = 0 to 2.0 percent.

Once approximate bitumen demand is estimated, the percentage of fresh bitumen to be added is calculated by subtracting the RAP bitumen content from the total bitumen demand. Based on aged bitumen viscosity and proportion of aged bitumen, the viscosity of fresh bitumen is decided. Finally, the job mix formula is arrived by conducting

tests by either Marshall or Hveem method. In Asphalt Institute method, quantity of fresh bitumen to be added is decided first and its viscosity is finalized subsequently. Also in Asphalt Institute method, the amount of RAP is prefixed. Similar procedure has been suggested by Roberts et. al. [29], where it is emphasized that the upper limit of RAP percentage in total mix should be specified. To estimate bitumen proportion, in some guidelines penetration [17, 25, 13] or shear modulus [19] is used as criteria instead of viscosity [2].

In another procedure proposed by Epps et al. [7, 6], the quantity of new aggregates to be added to achieve the specified gradation, is first decided based on recycled aggregate gradation. The bitumen demand is estimated using the new mix proportion. The mix thus prepared using bitumen modifier, recycled aggregates and new aggregates and is tested using Marshall or Hveem method. Also some other tests like stability test, water susceptibility tests etc. are recommended before deciding upon the final mix proportions. In this procedure also, since the aggregate gradation is adjusted first, and then the quantity of bitumen to be added, the viscosity (or grade) of fresh bitumen automatically becomes fixed.

2.6.2 Closing remarks

By fixing initially the RAP percentage to be used, as is done in some methods, one looses the opportunity to decide to what extent the RAP could have been used. Hence utilization of RAP to the fullest extent may not have been achieved. Also, in most of the procedures, the recycled mix design recommends the viscosity of fresh bitumen to be used. This may give rise to a difficult situation, if the particular grade of bitumen having recommended viscosity is not available in the market - especially with reference to Indian condition where only limited varieties of bitumen grades are available. This has prompted the present investigator to develop a recycled mix design process where (i) the amount of RAP to be used is not pre-fixed and (ii) grade of the fresh bitumen to be used is pre-fixed.

2.7 Closing Remarks

This chapter discussed various aspects of bituminous pavement recycling like bitumen chemistry and constituents effect on characterization. Also recycling methods and mix design procedures have been discussed. From the above discussion it is clear that constituents of bitumen affect the performance of the mix. Mix design procedures presently used turns out to be inefficient from point of recycling old materials. Hence an attempt is made to develop mix design procedure which can take care of this drawback.

Chapter 3

Methodology

3.1 Introduction

As mentioned earlier, RAP is deteriorated asphalt mix that contains aged bitumen and aggregates. Hence its performance is poorer when compared to the fresh mix. The purpose of the asphalt recycling is to regain the properties of the RAP, such that it tends to perform as good as fresh mix. Thus, the process of asphalt recycling involves mixing of the RAP, fresh bitumen, rejuvenator and new aggregates in suitable proportions. Rejuvenators are low viscosity oily substance, which helps to bring down the high viscosity of aged bitumen. The requirements of the recycled mix can be summarized as follows:

- The quantity of old aggregates and new aggregates are to be adjusted in such a way the resultant gradation of aggregates conforms to the specified gradation.
- The quantity of the aged bitumen, fresh bitumen and the rejuvenators are to be adjusted in such a way that the resultant viscosity becomes equal to the desirable viscosity at operating temperature during construction. Some other parameters (for example complex shear modulus etc.) may be chosen instead of viscosity, if desired.

- The total quantity of bitumen should be adjusted in such a way that it satisfies the optimum bitumen quantity of the target mix.
- The other mix design parameters like voids in mineral aggregates (VMA), air voids (VA) etc should also be satisfied.

3.2 Proposed Mix Design

3.2.1 Assumptions

Keeping in mind the above mentioned requirements, new method for hot mix recycling is proposed based on following assumptions.

- A three component mixture is assumed constituted with RAP, new aggregates and fresh bitumen. Rejuvinator has not been considered in present study. It is assumed that aged bitumen (from RAP) and fresh bitumen get mixed with each other perfectly.
- It is assumed that optimum bitumen content of recycled mix is known beforehand. This preliminary estimate of optimum bitumen content is necessary for calculating the constituent proportion of the recycled mix. In present study, approximate bitumen content is estimated based on surface area method is given in Equation 2.1.

3.2.2 Basic approach

Figure 3.1 give the flow chart of the procedure adopted. It is also explained step by step in the following

- Samples are procured from the old pavement that is to be recycled.

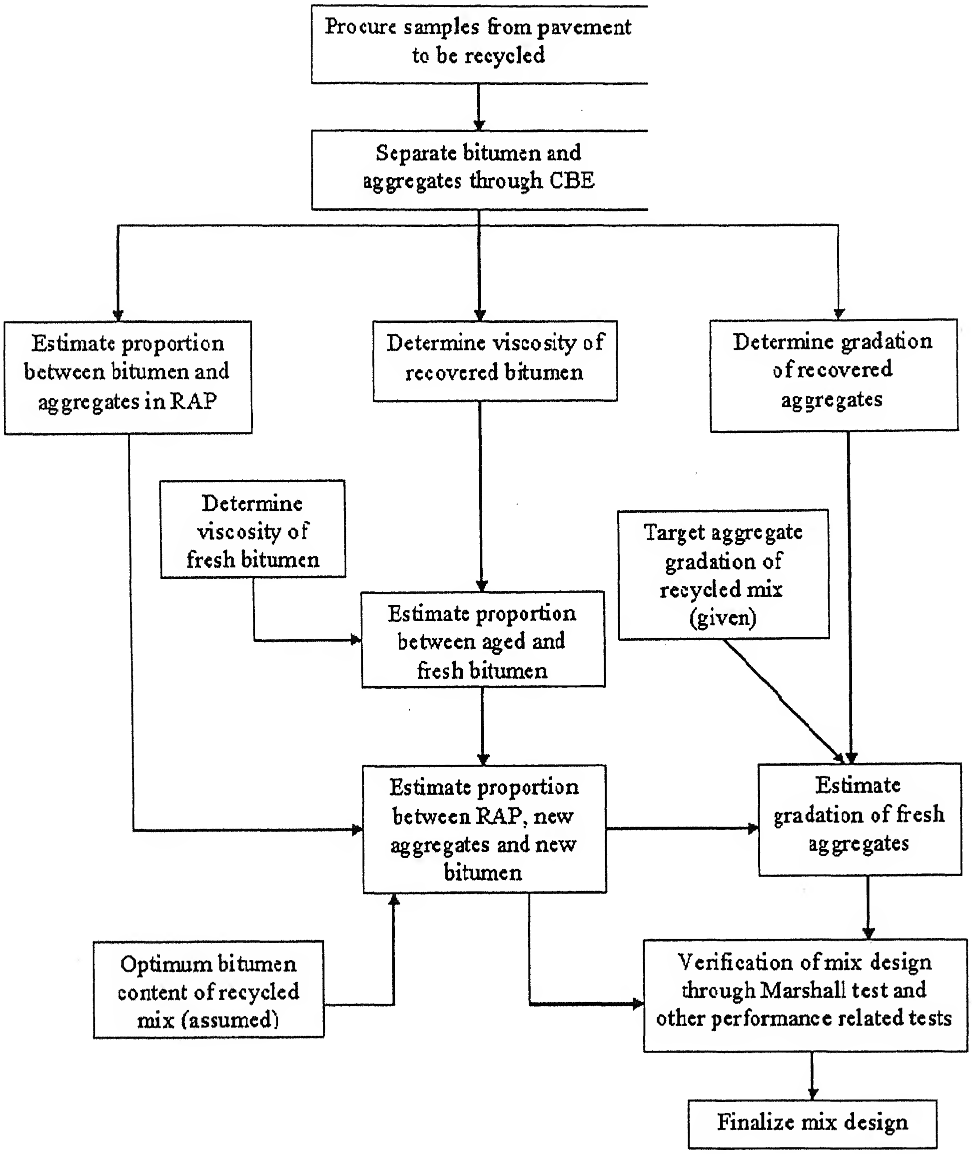

Figure 3.1: Flow chart for proposed laboratory mix design procedure for recycled mix

- Bitumen and aggregates are separated from the old mix using Centrifuge Bitumen Extractor (CBE).

- From the materials obtained, average bitumen content of old mix and the gradation of the old aggregates are found out.

- Recovered bitumen is tested for viscosity at the desired temperature. Also, the viscosity of the fresh bitumen is found at same temperature.

- In the next step, the proportion of the fresh and aged bitumen is estimated by using viscosity mixing rule, so that the resultant mix achieves the target viscosity[1] at suitable temperature. The present study uses the formula used by Asphalt Institute [2, 23] and ASTM 4887 [4] and is given below.

$$ln(\eta_t) = x_o \ln(\eta_o) + x_n \ln(\eta_n) \tag{3.1}$$

where η_t = target viscosity, x_o = weight/volume fraction of aged bitumen, η_o = viscosity of aged bitumen, x_n = weight/volume fraction of fresh bitumen/ recycling agent, η_n = viscosity of fresh bitumen/ recycling agent

- Once the proportion between aged and fresh bitumen is found, from consideration of presence of aged bitumen in total mix, proportion of RAP in recycled mix is determined. Thus the quantity of new aggregates to be added can also be determined. This has been explained schematically in Figure 3.2.

- Further, considering gradation of target mix and old mix, gradation of new aggregate can be obtained.

3.2.3 Estimation of mix composition

The previous section (Section 3.2.2) presented the principle of the proposed mix design. Based on this principle the following paragraphs discuss further on how to estimate

[1] Specified based on desirable properties of mix like workability, uniform mixing with aggregates etc.

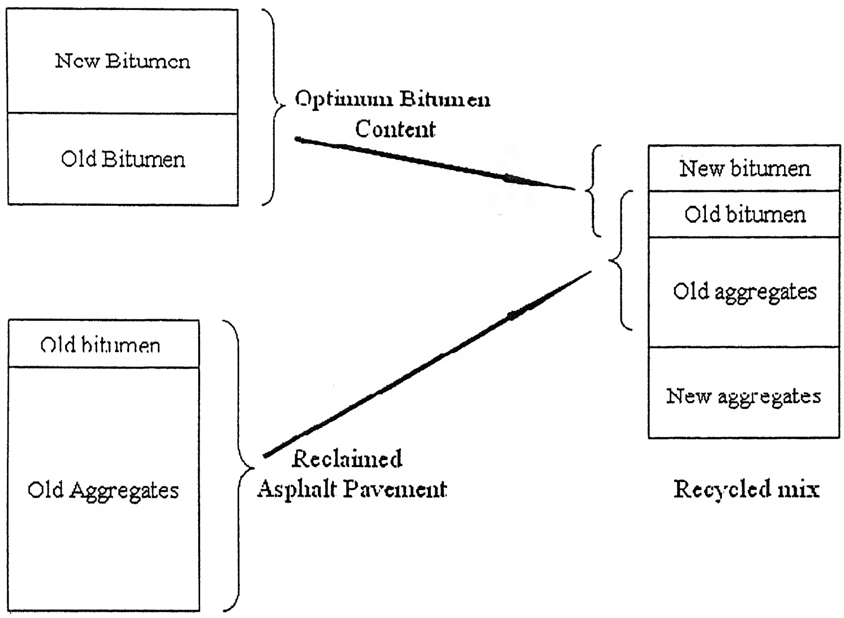

Figure 3.2: Schematic diagram for composition of recycled mix

the constituent proportions.

3.2.3.1 Solution obtained using direct method

Formulation

The parameters that are known/assumed initially are target viscosity of bitumen in recycled mix (η_t), viscosity of aged bitumen (η_o), viscosity of fresh bitumen (η_n), percentage of bitumen in recycled mix (P_b^R), percentage of bitumen in old mix (P_b^{RAP}).

The percentages of the components need to be determined are percentage of fresh bitumen in recycled mix (P_{nb}^R), percentage of RAP in recycled mix (P_{RAP}^R), percentage of new aggregates in recycled mix (P_{na}^R).

Consider a two component system of aged bitumen and fresh bitumen, where proportion of aged bitumen (p_{ob}) and proportion of fresh bitumen (p_{nb}) are unknown. It should be noted that p_{ob} and p_{nb} have been expressed as fractions whereas rest of the

quantities have been expressed as percentages.

From Equation 3.1 we have, $ln(\eta_t) = p_{ob}\ln(\eta_o) + p_{nb}\ln(\eta_n)$.

Here $p_{ob} + p_{nb} = 1$. Substituting the same in above equation and rearranging we get,

$$p_{ob} = \frac{(ln\ \eta_t - ln\ \eta_n)}{(ln\ \eta_o - ln\ \eta_n)} \tag{3.2}$$

$$p_{nb} = \frac{(ln\ \eta_t - ln\ \eta_o)}{(ln\ \eta_n - ln\ \eta_o)} \tag{3.3}$$

Hence from the viscosity considerations, proportion between aged bitumen and fresh bitumen is found to be p_{ob}:p_{nb}.

Therefore percentage of fresh bitumen in recycled mix =

$$P_{nb}^R = p_{nb} \times P_b^R \tag{3.4}$$

Similarly percentage of aged bitumen in recycled mix =

$$P_{ob}^R = p_{ob} \times P_b^R \tag{3.5}$$

Since P_{RAP}^R is percentage of RAP used in recycled mix, aged bitumen present is given by

$$\left(\frac{P_b^{RAP}}{100}\right) \times P_{RAP}^R \tag{3.6}$$

Equating Equation 3.6 with Equation 3.5, we get

$$P_{RAP}^R = \frac{(P_{ob}^R \times 100)}{P_b^{RAP}} = \frac{(p_{ob} \times P_b^R \times 100)}{P_b^{RAP}} \tag{3.7}$$

Therefore percentage of new aggregates in recycled mix is

$$P_{na}^R = 100 - \left(P_{RAP}^R + P_{nb}^R\right). \tag{3.8}$$

Finally the percentages of fresh bitumen, RAP and new aggregates can be obtained from Equation 3.4, Equation 3.7, Equation 3.8 respectively. These have been tabulated again in Table 3.1 for sake of convenience.

Table 3.1: Formulae for calculating recycled mix component percentages by direct method

Percentage of fresh bitumen (P_{nb}^R)	$p_{nb} \times P_b^R$
Percentage of RAP (P_{RAP}^R)	$\frac{(p_{ob} \times P_b^R \times 100)}{P_b^{RAP}}$
Percentage of new aggregates (P_{na}^R)	$100 - (P_{RAP}^R + P_{nb}^R)$

Comparison with Asphalt Institute method

Asphalt Institute [23] gives the formulas for calculating the percentages of different components. The notations used by them and notations used in the present work has been tabulated in Table 3.2.

Table 3.2: Comparison of notations used in Asphalt Institute method and the present work

Component	Asphalt Institute notations	Notations used in present work
Percentage of RAP in recycled mix	P_{sm}	P_{RAP}^R
Percentage of bitumen in recycled mix	P_b	P_b^R
Percentage of bitumen in old mix	P_{sb}	P_b^{RAP}
Percentage of fresh bitumen in recycled mix	P_{nb}	P_{nb}^R
Percentage of new aggregates in recycled mix	P_{na}	P_{na}^R

The formulae for constituent proportions given by Asphalt Institute is verified with the obtained formulae as presented in Table 3.1 and found to be basically same. However set of known and unknown parameters are different in Asphalt Institute method than present proposed method.

Design charts

This section studies graphically the formulae presented in Table 3.1. From Figures 3.3

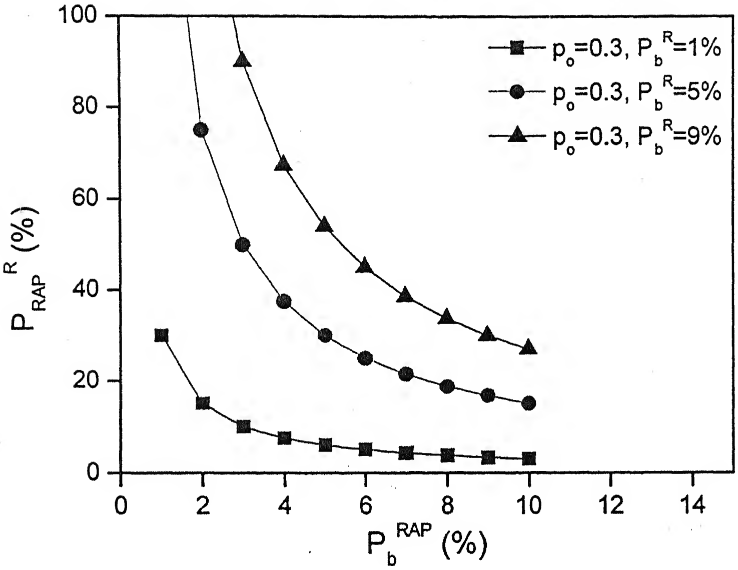

Figure 3.3: Design chart to find out RAP percentage (p_o=0.3)

and 3.4 it is seen that for same design bitumen content in recycled mix (i.e. OBC), as bitumen content in RAP increases, less amount of RAP needs to be added. Hence the curves show a decreasing trend. As proportion of aged bitumen increases, higher quantity of RAP needs to be added. Hence the curve shifts upwards.

Similar graph has been plotted for finding percentage of new aggregates to be added. The same has been presented in Figures 3.5 and 3.6.

3.2.3.2 Solution obtained using Linear Programming

The formula for arriving at proportions (percentages) of different recycled mix components by direct approach has been presented in Section 3.2.3.1. This section extends the formulation towards a more general situation. As a general situation the target viscosity (η_t) could be assumed as a range (η_t^l to η_t^u), instead of a fixed value. Similarly, since P_b^R (=OBC) value of recycled mix is not known before hand, it would be logical to assume P_b^R over a range (i.e. $(P_b^R)^l$ to $(P_b^R)^u$). Thus the formulation presented in

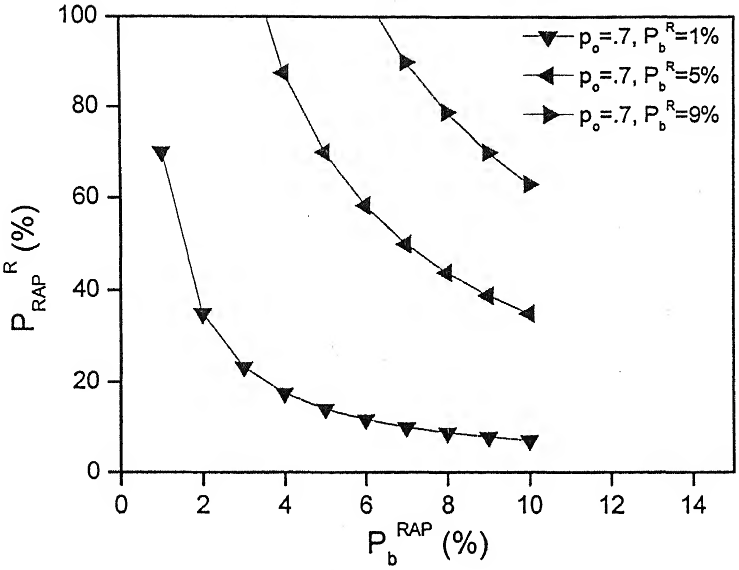

Figure 3.4: Design chart to find out RAP percentage (p_o=0.7)

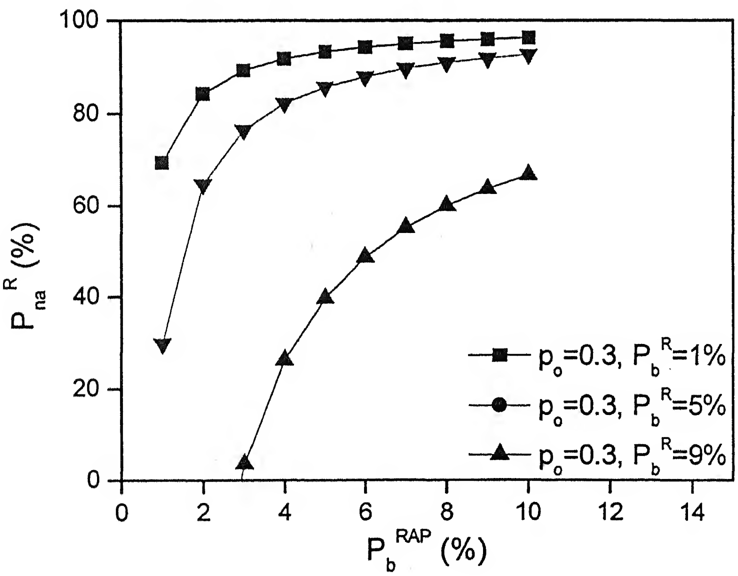

Figure 3.5: Design chart to find amount of new aggregates to be used (p_o=0.3)

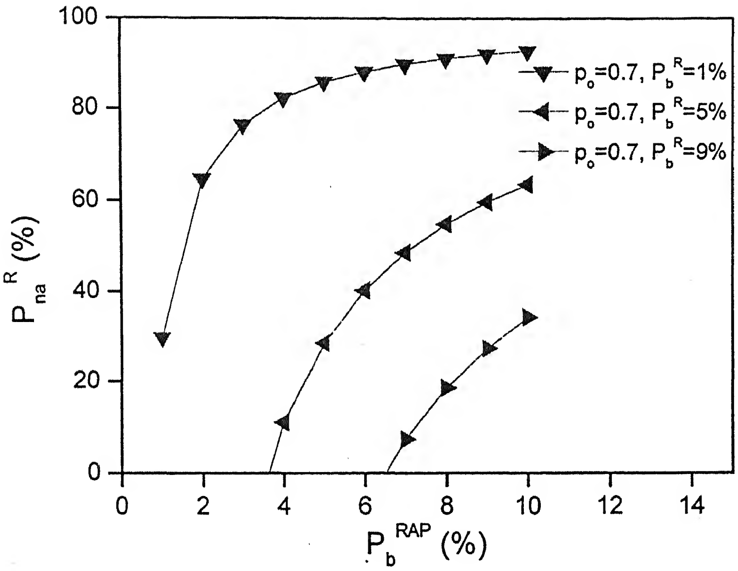

Figure 3.6: Design chart to find amount of new aggregates to be used (p_o=0.7)

Section 3.2.3.1 can be expressed in the form of a linear programming (LP) formulation and is presented below.

Constraints

Equations 3.9 and 3.10 put constraints on target viscosity at specified temperature.

$$\frac{(ln\ \eta_o \times (\frac{P_b^{RAP}}{100}) \times P_{RAP}^R) + (ln\ \eta_{nb} \times P_{nb}^R)}{((\frac{P_b^{RAP}}{100}) \times P_{RAP}^R) + P_{nb}^R)} \leq ln\ \eta_t^u \tag{3.9}$$

$$\frac{(ln\ \eta_o \times (\frac{P_b^{RAP}}{100}) \times P_{RAP}^R) + (ln\ \eta_{nb} \times P_{nb}^R)}{((\frac{P_b^{RAP}}{100}) \times P_{RAP}^R) + P_{nb}^R)} \geq ln\ \eta_t^l \tag{3.10}$$

The Equations 3.11 and 3.12 put constraint on the P_b^R value. Thus

$$((\frac{P_b^{RAP}}{100}) \times\ P_{RAP}^R) + (P_{nb}^R) \leq (P_b^R)^u \tag{3.11}$$

$$((\frac{P_b^{RAP}}{100}) \times \ P_{RAP}^R) + (P_{nb}^R) \geq (P_b^R)^l \tag{3.12}$$

where $(P_b^R)^l$ = Lower limit on percentage of bitumen in recycled mix, $(P_b^R)^u$ = Upper limit on percentage of bitumen in recycled mix.

It is obvious that sum of percentage of all individual components (i.e. P_{RAP}^R, P_{nb}^R and P_{na}^R) in recycled mix should be equal to 100. The same has been given in Equation 3.13.

$$P_{RAP}^R + P_{nb}^R + P_{na}^R = 100 \tag{3.13}$$

Also the percentage of different components cannot be less than or equal to zero. Nonnegative constraints have been given in Equation 3.14 and 3.15.

$$P_{RAP}^R > 0 \tag{3.14}$$

$$P_{nb}^R > 0 \tag{3.15}$$

$$P_{na}^R \geq 0 \tag{3.16}$$

Figure 3.7 shows a 2-D plot of the feasible zone obtained by using the above mentioned constraints (Equation 3.9 through Equation 3.12). Since it is a 2-D plot constraints indicated by Equations 3.13 and 3.16 could not be plotted in Figure 3.7.

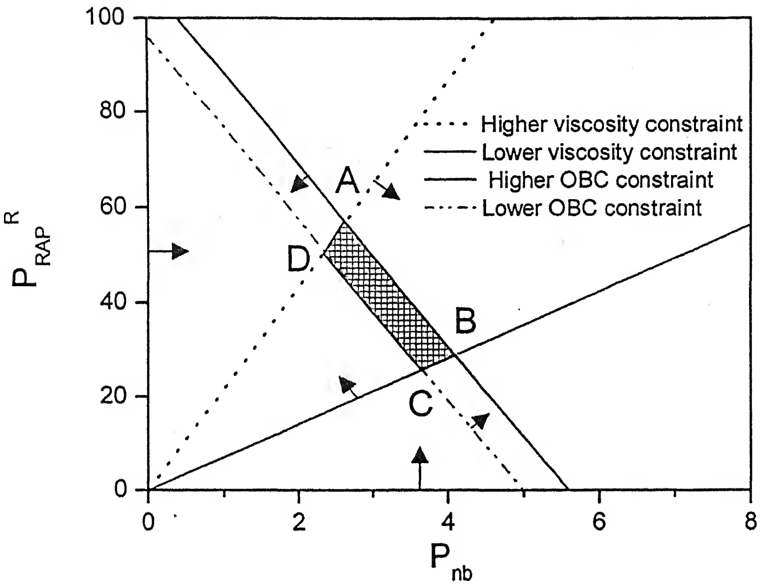

Figure 3.7: A 2-D plot of feasible zone considering mix design constraints

Objective function

The objective function could be the following.

- Maximization of RAP: One may be interested to maximize the quantity of RAP so that more amount of material could be recycled. Thus the objective function is

$$Max \ \{P^R_{RAP}\}$$

- Minimization of total material cost: One may be interested to minimize the total material cost. Thus the objective function can be written as

$$Min \ \{(C_{RAP} \times P^R_{RAP}) + (C_{na} \times P^R_{na}) + (C_{nb} \times P^R_{nb})\}$$

where C_{RAP} = Cost of RAP per unit quantity, C_{na} = cost of new aggregate per unit quantity, C_{nb} = cost of fresh bitumen per unit quantity.

Since the cost is assumed as linear combination of the component percentages, this objective function automatically merges to the previous objective function if cost of RAP is the least

3.2.4 Formulation: determination of new aggregate gradation

The quantity of aggregate to be added has already been obtained in Section 3.2.3.1. Some time there is need of adjustment of aggregate gradation. The reasons could be the following:

- Under the action of vehicles, the aggregates used in pavement may get crushed. Thus with time the materials become under sized when compared to construction stage.
- Old mix might have been designed as different mix according to gradation and specifications in practice at that time. If those specifications have been revised there is need for adjustment of aggregate gradation.

The gradation of old recovered aggregates can determined by sieve analysis. The target gradation is assumed from the relevant specifications. Once the proportions of new aggregates and old aggregates is known, gradation of new aggregates can be determined. Figure 3.8 shows this graphically. The formulation of this method has been given below.

Cumulative percentage passing of old aggregates can be represented in form as column matrix $\mathbf{P}_i^o$ where i is the ith sieve size. Similar matrices can be constructed for upper limit and lower limit on target gradation. Hence column matrix of old aggregate gradation, new aggregate gradation, Upper limit on target gradation and lower limit on target gradation can be represented by $\mathbf{P}^o, \mathbf{P}^n, \mathbf{T}^u$ and $\mathbf{T}^l$.

The conditions to be satisfied in order to conform the gradation requirements are as follows.

$$(\mathbf{P}^o \times \mathrm{p}_o) + (\mathbf{P}^n \times \mathrm{p}_n) \geq \mathbf{T}^l \tag{3.17}$$

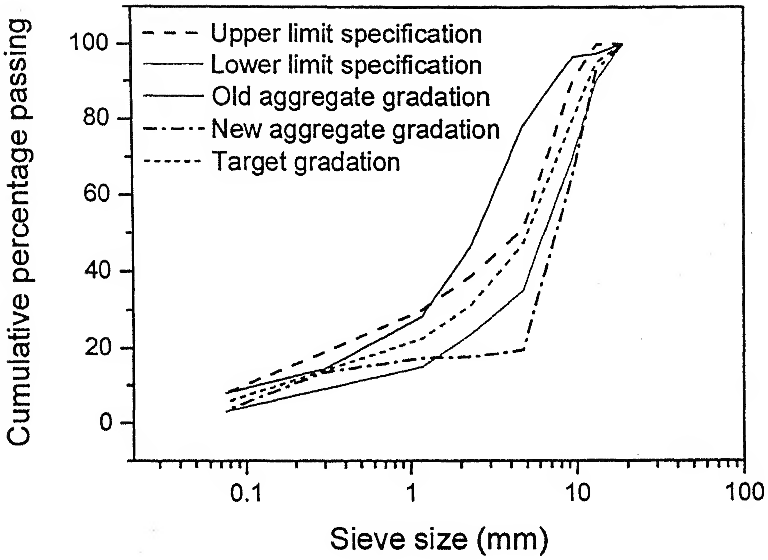

Figure 3.8: Determination of new aggregate gradation

$$(\mathrm{P}^o \times \mathrm{p}_o) + (\mathrm{P}^n \times \mathrm{p}_n) \leq \mathrm{T}^u \tag{3.18}$$

By assuming resultant gradation to pass through midpoint of upper limit and lower limit, above equations can be transformed into equality equation. Thus,

$$\mathrm{T}^m = \frac{(\mathrm{T}^l + \mathrm{T}^u)}{2} \tag{3.19}$$

$$(\mathrm{P}^o \times \mathrm{p}_o) + (\mathrm{P}^n \times \mathrm{p}_n) = \mathrm{T}^m \tag{3.20}$$

Reorganizing the above equation we get,

$$\mathrm{P}^n = \frac{\mathrm{T}^m - (\mathrm{P}^o \times \mathrm{p}_o)}{\mathrm{p}_n} \tag{3.21}$$

In the above matrix it should be noted that i^{th} element should be less than $(i-1)^{th}$ element. If this is not the case the matrix $\mathbf{T}^m$ is adjusted such that it satisfies above condition within the upper limit and lower limit gradation as specified.

3.3 Example

In this section an example for constituent proportioning of recycled mix design has been given. Problem has been solved both by direct method (Section 3.2.3.1) and using LP (Section 3.2.3.2).

3.3.1 Problem statement

It is proposed to recycle RAP collected from a road stretch. Bitumen content present in RAP is found to be 5.21% and viscosity of aged bitumen is measured to be 6240 mPa sec. Gradation of recovered aggregate is given in Table 3.3.

Table 3.3: Gradation of extracted aggregates

Sieve Size (mm)	19	13.2	9.5	4.75	2.36	1.18	0.6	0.075
Cumulative percentage passing	100.00	94.58	84.51	67.44	33.00	19.47	5.86	2.00

Viscosity of fresh bitumen intended to be used has a viscosity of 1140 mPa sec at reference temperature of 100^0C. Viscosity of bitumen in recycled mix is found to be satisfactory over a range of 1800 mPa - 2800 mPa sec at reference temperature. The OBC is assumed to be in range of 5.0% to 5.6%. Desired gradation of recycled mix choosen as SDBC specifcation of MORT&H [31] is given in Table 3.4.

Estimate the proportion of RAP, new aggregates and fresh bitumen in recycled mix.

Table 3.4: Gradation specification for SDBC

Sieve Size (mm)	19	13.2	9.5	4.75	2.36	1.18	0.6	0.075
Upper limit	100.00	100.00	90.00	51.00	39.00	30.00	19.00	8.00
lower limit	100.00	90.00	70.00	35.00	24.00	15.00	9.00	3.00

3.3.2 Solution: determination of constituent proportion

Assuming the recycled mix gradation passes through mid point gradation of the given specifications (Table 3.4), approximate bitumen demand can be calculated from Equation 2.1. Taking a=68.5, b=(31.5-5.5)=26, c=5.5, K=.19, F=1 and substituting in Equation 2.1 we get P_b^R= 5.6125% $\approx$ 5.6%

From given details, P_b^{RAP}=5.21%, η_o=6240 mPa sec, η_n=1140 mPa sec, η_t^u=2800 mPa sec, η_t^l=1800 mPa sec

3.3.2.1 Case 1: solution by direct method

Assume η_t =2300 mPa sec (average of 2800 and 1800)

Proportion of aged bitumen in mixture of aged bitumen and fresh bitumen is obtained using Equation 3.2, $p_{ob} = \frac{(ln\ 2300 - ln\ 1140)}{(ln\ 6240 - ln\ 1140)} = 0.413$.

Thus the proportion of fresh bitumen in mixture of aged bitumen and fresh bitumen = 1- 0.413 = 0.587.

Assume P_b^R (OBC)= 5.6%

From Equation 3.4,
percentage of fresh bitumen in recycled mix = P_{nb}^R = 0.587 $\times$ 5.6= 3.288%.

From Equation 3.7,
percentage of RAP in recycled mix = $P_{RAP}^R = \frac{\{0.413 \times 5.6 \times 100\}}{5.21}$ = 44.379%.

From Equation 3.8, percentage of new aggregates in recycled mix

$= P^R_{na} = 100 - \{50.096 + 3.288\} = 52.333\%.$

Thus proportions of fresh bitumen, RAP and new aggregates are 3.288%, 44.379% and 52.333% respectively.

3.3.2.2 Case 2: Solution using LP approach for cost minimization

Considering the objective function as cost minimization it can be written as:

$$\text{Minimize } \{(C_{RAP} \times P^R_{RAP}) + (C_{na} \times P^R_{na}) + (C_{nb} \times P^R_{nb})\}$$

From Equation 3.9, we have

$$\frac{(ln\ 6240 \times (\frac{5.21}{100}) \times P^R_{RAP}) + (ln\ 1140 \times P^R_{nb})}{((\frac{5.21}{100}) \times P^R_{RAP}) + P^R_{nb})} \leq ln\ 2800$$

$$0.0417P^R_{RAP} - 0.8986P^R_{nb} < 0 \tag{3.22}$$

From Equation 3.10, we have

$$\frac{(ln\ 6240 \times (\frac{5.21}{100}) \times P^R_{RAP}) + (ln\ 1140 \times P^R_{nb})}{((\frac{5.21}{100}) \times P^R_{RAP}) + P^R_{nb})} \geq ln\ 1800$$

$$0.0647P^R_{RAP} - 0.4568P^R_{nb} > 0 \tag{3.23}$$

From Equation 3.11, we have

$$((\frac{5.21}{100}) \times \ P^R_{RAP}) + (P^R_{nb}) \leq 5.6\%$$

$$0.0521\ P^R_{RAP} + P^R_{nb} \leq 5.6 \tag{3.24}$$

From Equation 3.12, we have

$$((\frac{5.21}{100}) \times \ P^R_{RAP}) + (P^R_{nb}) \geq 5.0\%$$

$$0.0521\ P^R_{RAP} + P^R_{nb} \geq 5.0 \tag{3.25}$$

Using above constraints (Equations 3.22 to 3.25) and other constraints stated earlier (Equations 3.13 to 3.15), the problem was solved using CPLEX software for following cases.

Scenario A: $C_{RAP} < C_{na} < C_{nb}$ The cost of different components are taken as C_{RAP} = Rs 500, C_{na} = Rs 800, C_{nb} = Rs 1000.

Scenario B: $C_{RAP} = C_{na}; C_{nb} < C_{na}; C_{nb} < C_{RAP}$ The cost of different components are taken as C_{RAP} = Rs 500, C_{na} = Rs 500, C_{nb} = Rs 250.

Scenario C: $C_{na} < C_{RAP} < C_{nb}$ The cost of different components are taken as C_{RAP} = Rs 800, C_{na} = Rs 500, C_{nb} = Rs 1000.

Scenario D: $C_{RAP} = C_{na}; C_{nb} > C_{na}; C_{nb} > C_{RAP}$ The cost of different components are taken as C_{RAP} = Rs 500, C_{na} = Rs 500, C_{nb} = Rs 1000.

The results have been tabulated in Table 3.5.

The optimum points of scenario A, B, C and D have been marked on Figure 3.7 as points A, B, C and D respectively.

If the cost of RAP is less, then in order to minimize total cost more amount of RAP needs to be used. Hence cost minimization in case of Scenario A would be a special case of RAP maximization also.

Scenario A represents a case where cost of RAP is least and fresh bitumen is highest. Hence RAP needs to be used more and fresh bitumen least. Hence point having higher viscosity and bitumen content would be selected as optimum point. Similarly scenario C is a case where cost of fresh bitumen is least and cost of RAP is highest. Hence more point representing lower viscosity and lower bitumen content will be selected as optimal.

3.3.2.3 Case 3: Solution using LP approach for RAP maximization

Here the objective is to maximize percentage of RAP. Hence objective function would be Max $\{P^R_{RAP}\}$.

The constraints would be as given in Equations 3.22 to 3.25 and Equations 3.13 to 3.15. Solving using optimization tool, the proportions of RAP, new aggregates and fresh bitumen are obtained as 56.849%, 40.513% and 2.638% respectively.

Values given above are matching with Case 2: Scenario A which is reflected in Table 3.5 also. This is because RAP maximization implies that higher viscosity of mix as well as higher amount of bitumen content is permitted.

Table 3.5: Comparison of constituent proportion obtained from direct method and LP

Method	P^R_{RAP} (%)	P^R_{nb} (%)	P^R_{na} (%)
Case 1: Direct method	44.379	3.288	52.333
Case 2: Scenario A, $C_{RAP} < C_{na} < C_{nb}$	56.849	2.638	40.513
Case 2: Scenario B, $C_{RAP} = C_{na}; C_{nb} < (C_{na}, C_{RAP})$	28.905	4.094	67.001
Case 2: Scenario C $C_{na} < C_{RAP} < C_{nb}$	25.808	3.655	70.537
Case 2: Scenario D, $C_{RAP} = C_{na}; C_{nb} > (C_{na}, C_{RAP})$	50.758	2.355	46.887
Case 3: RAP maximization	56.849	2.638	40.513

3.3.3 Solution: determination of aggregate gradation

Consider the mixture of old aggregates and new aggregates. In this mixture proportion of old aggregates is

$$p_{oa} = \frac{(44.379-2.312)}{((44.379-2.312)+52.333)} = 0.4456$$

and proportion of new aggregates is

$$p_{na} = \frac{(52.333)}{((44.379-2.312)+52.333)} = 0.5544.$$

Cumulative percentage passing of old aggregates can be represented in form as column matrix $\mathbf{P}_i{}^o$ where i is the i^{th} sieve size. Similar matrices can be constructed for upper limit ($\mathbf{T}^u$) and lower limit ($\mathbf{T}^l$) on target gradation. These have been given below:

$$\mathbf{P}_i{}^o = \begin{pmatrix} 100 \\ 94.58 \\ 84.51 \\ 67.44 \\ 33.00 \\ 19.47 \\ 5.86 \\ 2.00 \end{pmatrix}, \quad \mathbf{T}^u = \begin{pmatrix} 100 \\ 100 \\ 90 \\ 51 \\ 39 \\ 30 \\ 19 \\ 8 \end{pmatrix}, \quad \mathbf{T}^l = \begin{pmatrix} 100 \\ 90 \\ 70 \\ 35 \\ 24 \\ 15 \\ 9 \\ 3 \end{pmatrix},$$

Conditions given in Equations 3.17 and gradul needs to be satisfied in order to conform the gradation requirements.

Using Equations 3.19 to 3.21, we get

$$P^n = \begin{pmatrix} 100 \\ 95.34 \\ 76.37 \\ 23.35 \\ 30.29 \\ 24.94 \\ 20.54 \\ 8.31 \end{pmatrix}$$

In the above matrix, it is to be noted that 4^{th} row number is less than 5^{th} row. Since this dosen't satisfy property of cumulative percentage passing, the above solution is unacceptable. In order to get a feasible solution, the increasing value of ${T_4}^m$ from 43 to 47. Thus we get the final gradation as,

$$P^n = \begin{pmatrix} 100 \\ 95.34 \\ 76.37 \\ 30.57 \\ 30.29 \\ 24.94 \\ 20.54 \\ 8.31 \end{pmatrix}$$

3.4 Closing Remarks

The constituent proportioning thus developed has been used to prepare recycled mix samples for further testing. The experimental investigation has been dealt in next chapter.

Chapter 4

Experimental Studies

4.1 Selection of Materials

Old pavement materials (i.e RAP) required for conducting experiments were selected from two locations one is road stretch which belongs to Kanpur Development Authority (KDA) and other from with in IIT K campus. Henceforth referred to as KDA sample and IIT K sample respectively. The criteria for selecting the location were aged and distressed pavement. The material selected was cleaned to remove organic matter if any.

4.2 Constituent Proportion

In present study, samples have been prepared using proportions arrived at by direct method (procedure explained in Section 3.3.2.1). The values taken in calculations are $P_b^R = 5.6\%$, $\eta_t = 2300$ mPa sec and $\eta_n = 1140$ mPa sec. The values of η_o and for KDA and IIT K samples are 6240 mPa sec and 4750 mPa sec respectively. Similarly values of P_b^{RAP} are 5.21% and 4.62%. The percentages of different components thus obtained using direct method has been presented in Table 4.1.

Table 4.1: Proportions of different components used in present study

Material	P^R_{RAP}	P^R_{nb}	P^R_{na}
KDA	44.379	3.288	52.333
IIT K	59.614	2.846	37.540

4.3 Material Processing and Test Plan

The RAP collected from these sources were used in two ways (as already mentioned in assumptions (Section 3.2.1)) in present study. These processes have been explained below:

However it may be noted that in hot central plant recycling only a fraction of bitumen present in RAP will actually melt and mix with fresh bitumen.

- one set of test samples are prepared by separating bitumen and aggregates and then mixing as per desired proportion. This is called Type 1 sample.
- In other set of test samples the RAP is broken into pieces and mixed directly with new aggregates and fresh bitumen. This is called Type 2 sample.

It is believed that in the realistic situation, is somewhere in between these two cases.

This type of material processing was adopted in the test plan because this represents the two extreme cases. Type 1 sample represents a situation where due to impact of drum rotation, part of old material will break down into smaller sized lumps but aggregate and bitumen are not separated out. Type 2 sample is a situation where bitumen will melt at high temperature and get mixed completely with fresh bitumen. To simulate this in laboratory extracted bitumen has been mixed with fresh bitumen in precalculated proportion and then added to aggregates. However in field condition, the scenario would be in between these two extremities.

In order to validate any mix design, performance of these mix needs to be checked. It has been recognized that main modes of failure of pavement layer are fatigue, rutting,

low temperature cracking. Fatigue and rutting being predominant modes of failure in Indian conditions, fatigue testing and static creep tests were conducted on the recycled mixes.

Table 4.2 gives a overview of the number of specimens that were used for different tests.

Table 4.2: Test plan indicating the number of samples tested

Type of Test	Source				
	KDA		IIT K		Fresh mix
	Type 1	Type 2	Type 1	Type 2	
Fatigue Test	10	10	10	10	10
Creep Test	8	8	8	8	10

4.4 Tests Conducted

4.4.1 Bitumen extraction

4.4.1.1 Details of equipment

CBE was used for extracting bitumen from RAP. CBE consists of a motor connected to a bowl shaped closed container. The arrangement is made such that the solvent containing bitumen comes out through channel leaving behind the aggregates, when rotated at high speed. Figure 4.1 shows photograph of the equipment.

4.4.1.2 Bitumen extraction (ASTM D-2172)

Typically extraction of bitumen involved soaking of known amount of RAP in solvents like benzene in container of centrifuge extractor for 30 minutes. After old pavement materials was left for soaking for above said duration, the motor was switched on. Due to high rotational speed of around 3600 rpm, the benzene along with bitumen came

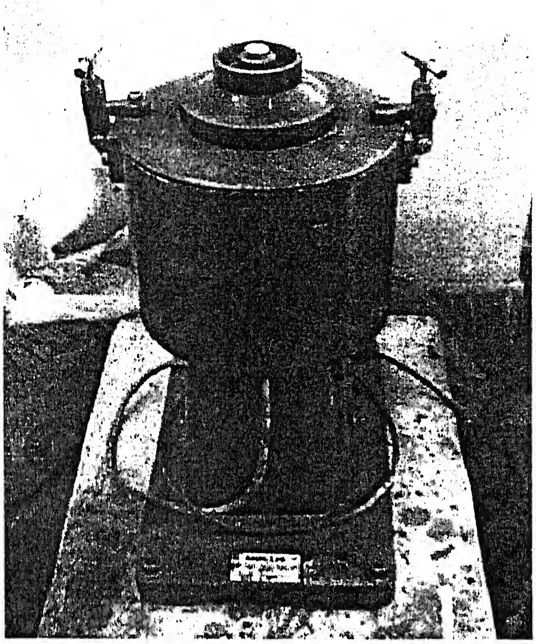

Figure 4.1: Centrifuge bitumen extractor

out. This process was repeated for further removal of bitumen from aggregates. The aggregates removed from the container was heated using oven. Oven dry aggregates are weighed again. Thus the bitumen content in RAP was found. Since aged bitumen was to be used again for testing, solution was heated to remove the benzene portion. It was heated at about 100^0C temperature such that no further bitumen ageing takes place.

4.4.2 Marshall tests

In the present study, mix design requirements laid down by MORT&H specifications [31] for Semi Dense Bituminous Concrete (SDBC) has been used. That means, the old mixes collected for the present study showed some other gradation, which was adjusted such that it conforms to the SDBC gradation of MORT&H. The specifications for SDBC is reproduced in Table 3.4 and 4.3.

Table 4.3: Marshall and volumetric specifications for SDBC mix design as per MORT&H [31]

Minimum Marshall stability	8.2 kN
Marshall flow	2 to 4 mm
VA in mix	3 to 5%
VMA	Min 14 %
VFB	65 to 78%

4.4.2.1 Mix preparation

In case of Type 1 material, the calculated amount of RAP as presented in Section 3.3 was heated in oven to a temperature of around 165^{0}C in hot oven. At the same time new aggregates are heated to a higher temperature than that of RAP using heater. Once they have attained above said temperature, old material and new aggregate are mixed together and hot fresh bitumen is added to this and mixed well.

In case of Type 2 material, the calculated amount of old aggregates and new aggregates are heated in oven to a temperature of around 165^{0}C in hot oven. Similarly mixture of aged bitumen and fresh bitumen are heated separately to a temperature of 150^{0}C, both are mixed to produce homogeneous mixture.

4.4.2.2 Sample preparation

For preparation of Marshall samples, automatic Marshall compactor was used. Photograph of the same has been given in Figure 4.2. It is compacted with 75 blows on each face [31].

4.4.2.3 Testing

After curing for 24 hours, the cores are removed from mould. The sample is weighed in air and water. After this, samples are kept in water bath for 30 minutes at 60°C. Then

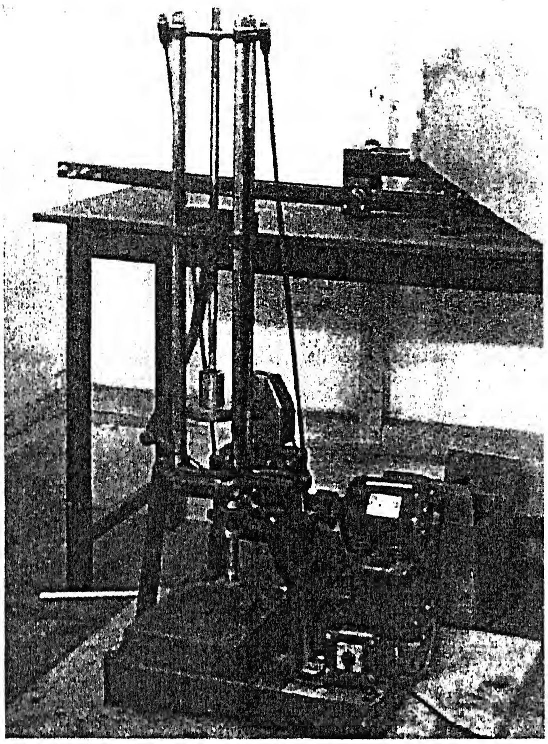

Figure 4.2: Marshall mould compactor

the sample is tested for stability and flow, using Marshall testing machine. Load is applied at rate of 50 mm/minute. The maximum load taken by the Marshall sample is reported as Marshall stability value and the corresponding deformation as flow value. Photograph of Marshall testing equipment is given in Figure 4.3.

4.4.3 Fatigue testing

4.4.3.1 Details of equipment

The rectangular beams of size 380mm × 78mm × 63mm casted, were used for testing for fatigue performance. For this purpose, fatigue testing machine fabricated at Transportation Engineering Laboratory, IIT Kanpur was used [8]. Photographic view of the machine is given in Figure 4.4.

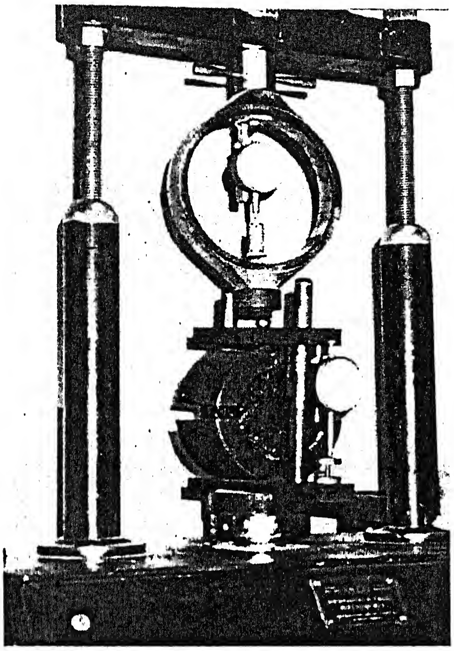

Figure 4.3: Marshall testing machine

It consists of a motor, cam, load cell, beam holding arrangement and data acquisition system. Motor is used to apply sinusoidal loading on the specimen. The cam arrangement is used to give displacement to the specimen. Cam is designed in such a way that the eccentricity can be varied. Such a mechanism is made so as to vary displacement which in turn changes strain in asphalt beam. The load cell is used in measuring the load applied. The beam holding arrangement is used to fix the beam rigidly in place. Data acquisition system used for acquiring data consists of LabView [20], commercially available software and hardware components.

The load cell intended for use was calibrated over a range of load. Voltage at different loads was recorded for developing calibration chart. This curve was used in measuring force exerted while conducting fatigue test. Typical calibration chart developed is shown in Figure 4.5. The negative load indicates compression.

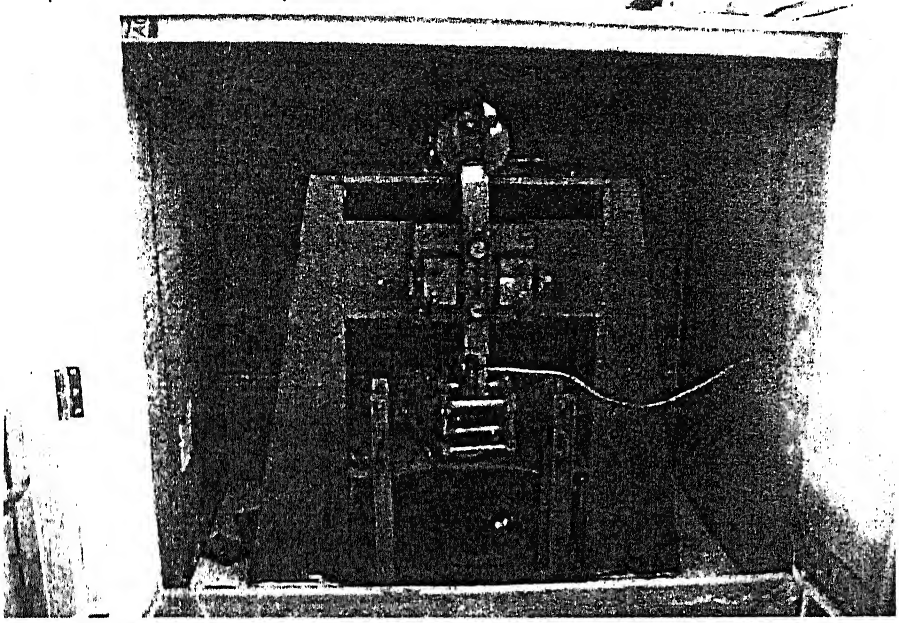

Figure 4.4: Fatigue testing machine

4.4.3.2 Sample preparation

The mixture obtained by procedure explained in Section 4.4.2.1 was poured into mould. Then it was compacted by giving 175 blows using standard Marshall hammer and an iron plate. The 175 blows was arrived at by comparing the Marshall sample density and rectangular beam sample density. The finished sample was left for curing for 1 day and then tested.

4.4.3.3 Testing

The cam was adjusted for a known eccentricity. After this the vertical displacement caused by this eccentricity is measured using LVDT/dial gauge. Then the cured beam was fixed to the fatigue testing equipment as shown in Figure 4.6. Once the motor is switched on the initial load applied on beam is noted. Similar exercise of load measurement was repeated at regular intervals till beam was deemed to have failed. Here failure criteria chosen was decrease of load to half the initial load. Similar procedure

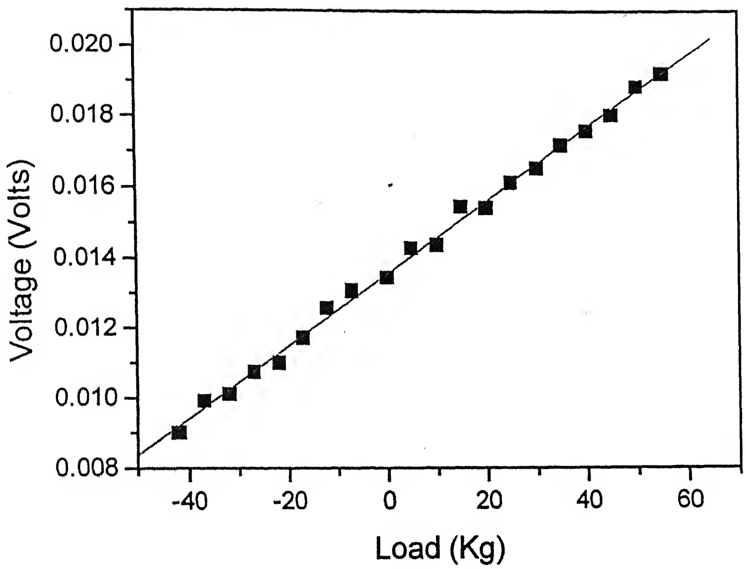

Figure 4.5: Variation of load cell output voltage versus applied load

was repeated using beams at different strain levels.

4.4.4 Creep testing

Under the action of vehicles plying on road, pavement layers under go permanent deformation. This is known as rutting. Static creep test is one of the tests which is said to characterize rutting. This involves application of known amount of static load for a specified duration at constant temperature. Strain in sample is noted at different time interval. In the present study recommendations made by Shell design manual [30] has been used which involves loading and unloading period of 1 hour at a temperature of 40^0C.

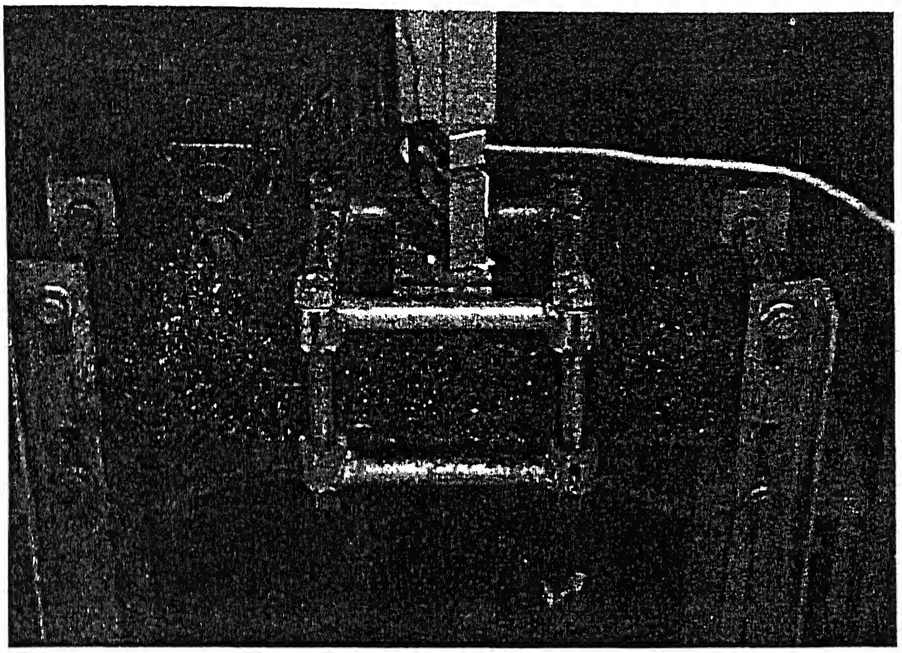

Figure 4.6: Arrangement of beam in loading frame

4.4.4.1 Details of equipment

For conducting creep tests, loading frame was fabricated in Transportation Engineering Laboratory, IIT Kanpur during present study. Schematic diagram and pictorial view has been shown in Figure 4.7 and Figure 4.8 respectively. It consists of a loading frame and a pair of dial gauges. Loading frame is designed in such a way that it transfers the load to the specimen axially. Also the dial gauges are placed independent of the loading frame. This helps in accurate measurement of deformation.

4.4.4.2 Sample preparation

The samples for creep tests were prepared in similar way the samples were prepared for Marshall testing. Mixtures obtained by process explained in Section 4.4.2.1 are used to prepare Marshall samples. For preparation of Marshall samples, automatic Marshall compactor was used. Photograph of the same has been given in Figure 4.2. It is compacted with 75 blows on each face [31]. Similar samples are casted at different

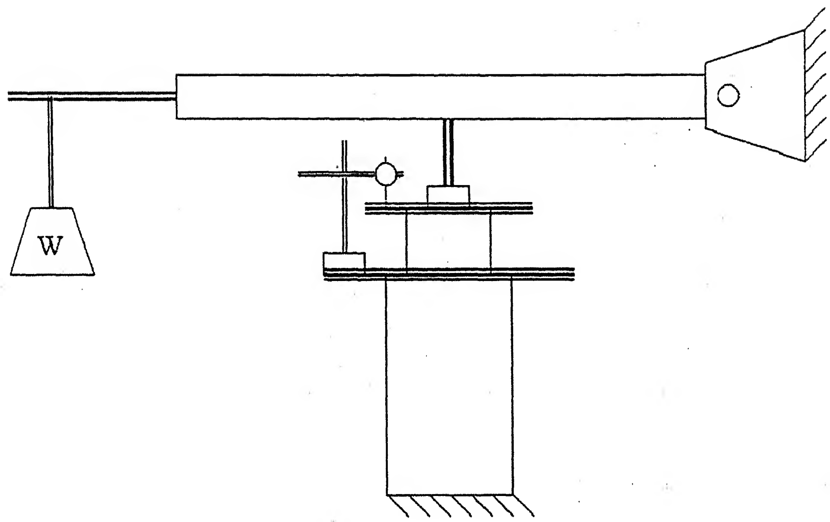

Figure 4.7: Schematic diagram of creep test setup

bitumen content.

4.4.4.3 Testing

The samples were placed horizontally in between the smooth surfaced ceramic plates. The dial gauges were fixed at two places on ceramic plates. Then the loading plate was placed over the sample. Then calculated amount of load was placed at end of loading frame such that stress of $0.1 MN/m^2$ is developed in sample. Then the displacements are noted at different time intervals using dial gauge. After a period of 1 hour, load was removed. Again the displacement was noted for next one hour. Typical response of asphalt mix under creep is given in Figure 4.9.

4.5 Closing Remarks

This chapter has presented the experimental investigation in terms of Marshall, fatigue and static creep test for KDA and IIT K samples. The next chapter presents the

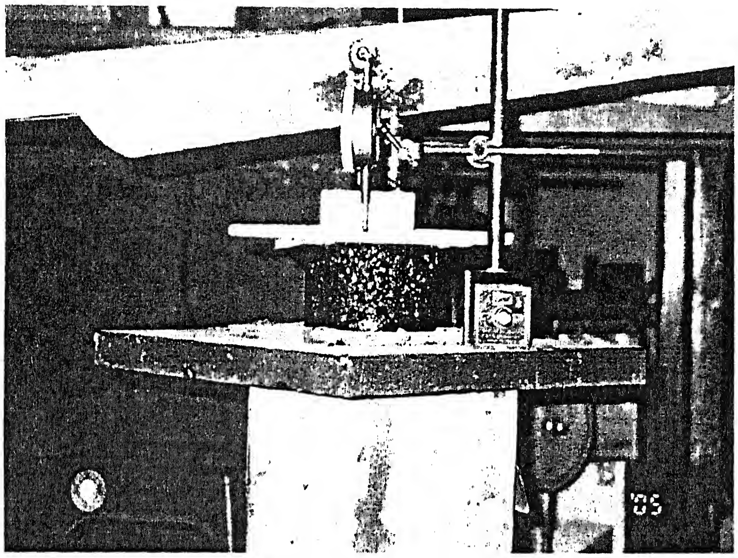

Figure 4.8: Closeup view of creep test setup

experimental results and analysis.

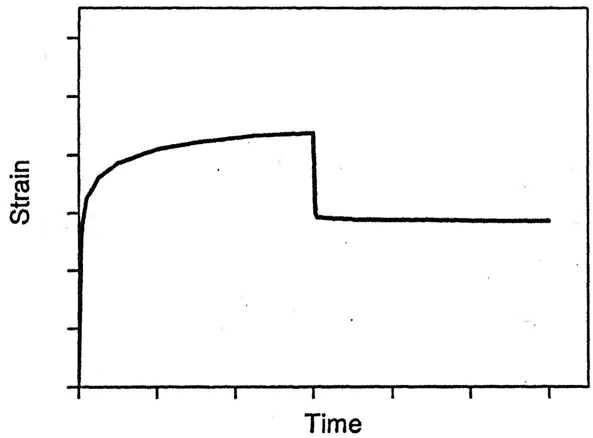

Figure 4.9: Variation of strain with time

Chapter 5

Results and Discussions

5.1 Properties of Materials Collected

As mentioned earlier, materials were collected from two sources namely KDA road and IIT K. Extracted bitumen as well as fresh bitumen intended to use was tested for properties like ductility, softening point, flash point, fire point and viscosity. The values obtained from these tests has been tabulated in Table 5.2. The gradation of recovered aggregates are presented in Table 5.1.

Table 5.1: Gradation of recovered aggregates

Sieve Size (mm)	19	13.2	9.5	4.75	2.36	1.18	0.6	0.075
KDA	100.00	94.58	84.51	67.44	33.00	19.47	5.86	2.00
IITK	100.00	93.83	80.78	61.84	32.64	21.47	9.45	3.76

5.2 Marshall Tests

Marshall tests were conducted on the material. Average values of the Marshall test parameters have been presented in Table 5.3.

Table 5.2: Properties of extracted and fresh bitumen

Test	Bitumen Type			
	Fresh		Extracted	
	80/100	60/70	IIT K	KDA
Ductility	67	77.2	10	11
Softening point (^{0}C)	49.5	50	78.5	69.5
Specific gravity	1.007	1.006	1.209	1.033
Flash point (^{0}C)	280	275	260	255
Penetration	87.5	64.75	18.75	26
Viscosity at 100^{0}C (mPa-sec)	1140	2320	4750	6240

Table 5.3: Comparison of Marshall test parameters

Marshall test parameters	MORT & H specifications [31]	KDA		IIT K	
		(Type 1)	(Type 2)	(Type 1)	(Type 2)
VA (%)	3 to 5	3.43	2.48	4.47	6.01
VMA (%)	Min 14	16.7	10.83	15.23	14.76
VFB (%)	65 to 78	79.5	77.20	70.74	59.19
Stability (kN)	$\geq$ 8.2	8.8	10.34	8.65	9.1
Flow (mm)	2 to 4	2	2.87	3.6	3.32

5.3 Fatigue Tests

As mentioned in Section 4.4.3.1, the rectangular beam samples are tested for their fatigue performance. The comparison of densities of the samples with respect to the Marshall density is presented in Table 5.4.

5.3.1 Variation of initial stiffness with temperature

It may be noted that the test temperatures for the beam samples varied slightly among the KDA, IIT K and the fresh mix samples. The temperature ranges during testing

Table 5.4: Details of sample density and degree of compaction

Material	Density (kg/m^3)			Average degree of compaction (%)
	Minimum	Maximum	Average	
Fresh mix	2072	2277	2130	94.34
KDA (Type 1)	1889	2185	2077	89.03
KDA (Type 2)	1993	2191	2047	84.79
IIT K (Type 1)	1810	2088	1979	90.40
IIT K (Type 2)	1927	2034	1982	85.27

Table 5.5: Fatigue testing test temperature details

Material	Test temperature (^{0}C)		
	Minimum	Maximum	Average
Fresh mix	24	31	27.8
KDA	28	32	30.6
IIT K	31	34	32.7

are presented in Table 5.5. Since, the comparison of the fatigue performance of the recycled mixes is to be done with respect to the fresh mixes, the fatigue performance curve of the fresh mix needs to be suitably adjusted to the average test temperatures of the KDA and IIT K samples. The following approach is proposed for this purpose.

A general fatigue equation can be represented as

$$N = k_0 \left(\frac{1}{\epsilon}\right)^{k_1} \left(\frac{1}{E}\right)^{k_2} \tag{5.1}$$

where N = Number of repetitions of load the beam can sustain before failure, ϵ = Initial tensile strain, E = Elastic modulus.

The values of the regression coefficients for various mixes are presented in Table 5.6. Now, the variation of the E value can be assumed in the form of $E(T) = E_0\ e^{-\lambda T}$, where E_0 = elastic modulus of mix at 0^0C. The variation between E(T) and T for various mixes are plotted in Figure 5.1. Thus, the values of the E_0 and λ for the fresh mix are obtained as 2.3E+05 and -0.0872 respectively. Similarly the E_0 and λ values can be

Table 5.6: Regression coefficients of fatigue equation

Material	Regression coefficients		
	k_0	k_1	k_2
Fresh mix	4.4371	1.5428	0.2067
KDA (Type 1)	0.0320	2.0164	0.2367
KDA (Type 2)	0.6890	2.1473	0.5367
IIT K (Type 1)	0.1871	1.3702	-0.3136
IIT K (Type 2)	22.5944	0.0681	-0.7570

obtained for other mixes. Table 5.7 presents these values for all the mixes. Using this relationship (between E(T) and T) it is possible to obtain the fatigue equation at any temperature. Thus, the fatigue equations for the fresh mix at the test temperatures of the KDA and IIT K samples are developed.

Table 5.7: Regression coefficients of initial stiffness versus temperature relationship

Material	E_o (MPa)	λ
Fresh mix	2.3E+05	-0.0872
KDA (Type 1)	3.0E+06	-0.2560
KDA (Type 2)	5.0E+08	-0.4292
IIT K (Type 1)	5.0E+07	-0.3414
IIT K (Type 2)	8.0E+07	-0.3603

5.3.2 Variation of fatigue life with initial tensile strain

The samples casted were tested for fatigue life at various strain levels. The raw data of fatigue test is given in Appendix B. The Figure 5.2 shows fatigue performance of mix prepared using new aggregates. Figures 5.3 and 5.4 presents variation of fatigue life with initial tensile strain in KDA and IIT K material respectively. Fatigue curve of fresh mix is also given for comparison which has been suitably adjusted (as mentioned in Section 5.3.1) for the average temperature at which KDA and IIT K samples are tested.

5.3.3 Discussions

From the Figures 5.3 and 5.4 it is clear that performance of recycled mixes are comparable to that of mixes prepared using new aggregates.

5.4 Creep Tests

The creep tests were conducted on specimens as explained in Section 4.4.4.

5.4.1 Variation of strain with time

The raw data of the creep test has been given in Appendix-C. Figure 5.5 show a typical graph of variation of strain with time in new aggregate mix. The maximum strain observed at end of 60 minute and 120 minute are noted down as total strain and permanent strain respectively. The difference of total strain and permanent strain is recorded as recoverable strain.

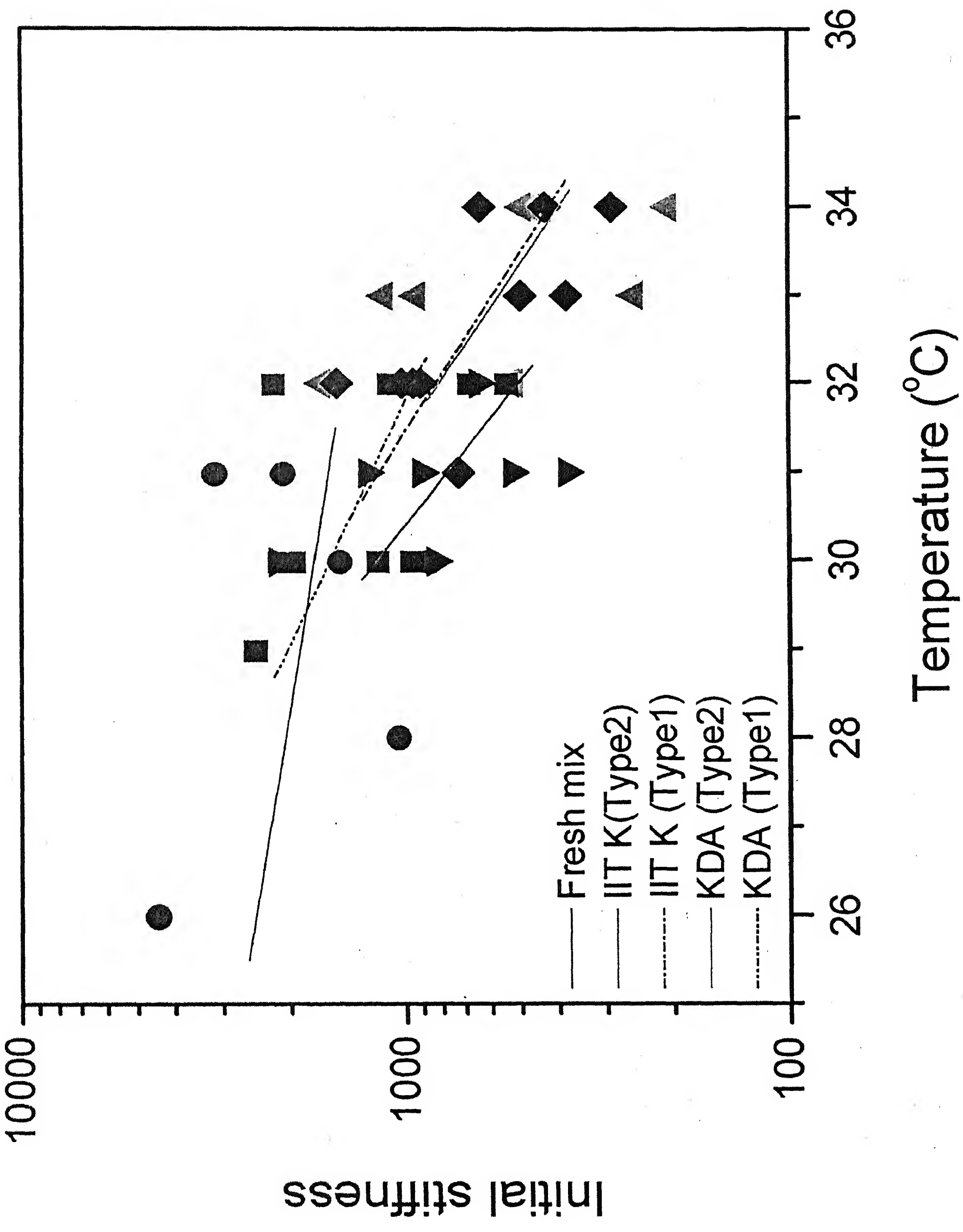

Figure 5.1: Variation of initial stiffness with temperature

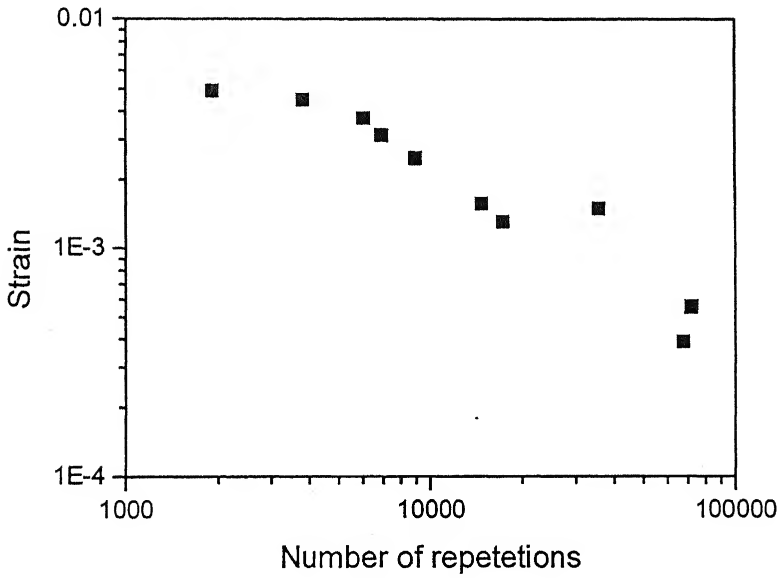

Figure 5.2: Variation of fatigue life with tensile strain, for fresh mix

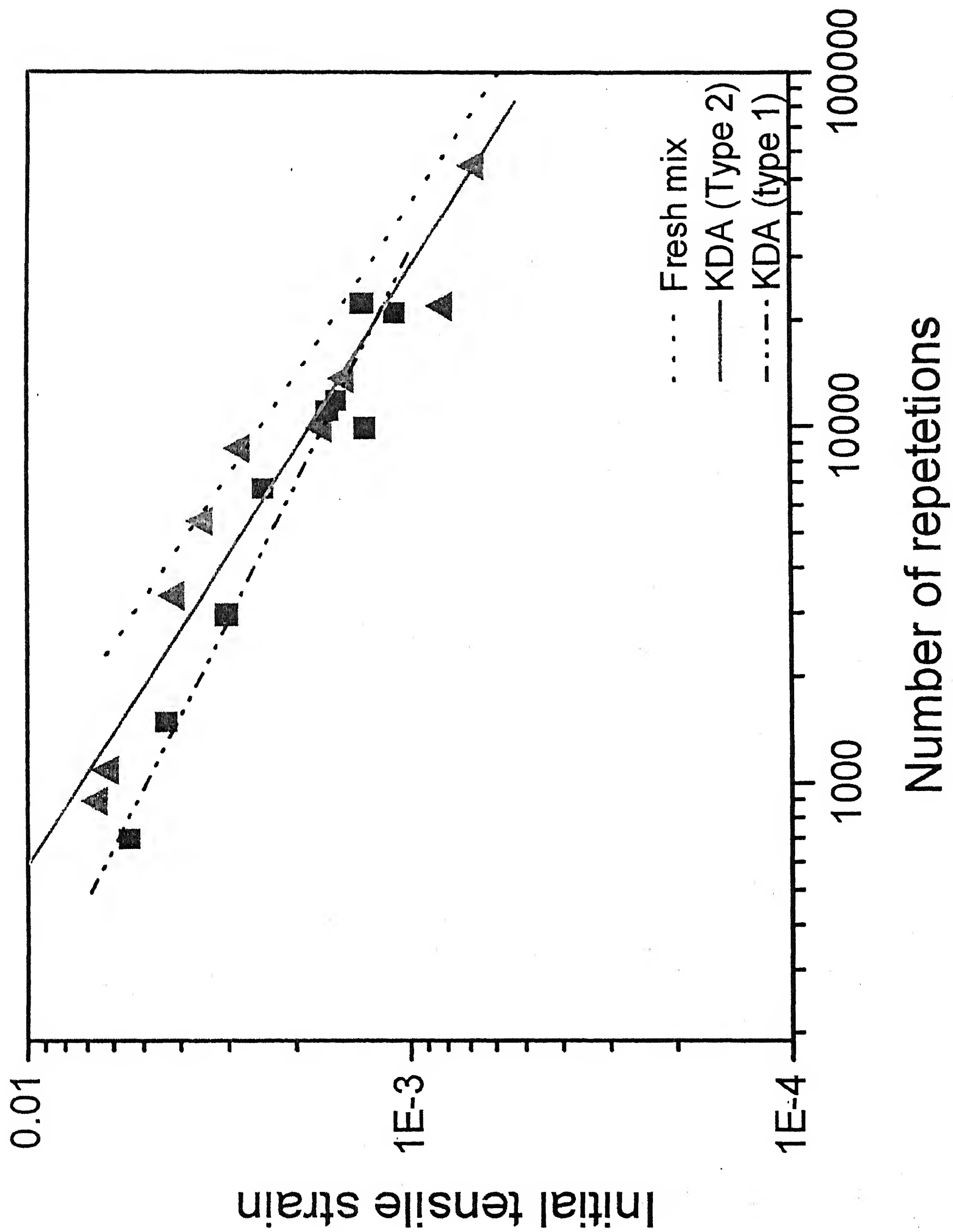

Figure 5.3: Comparison of fatigue performance of KDA mixes with fresh mix

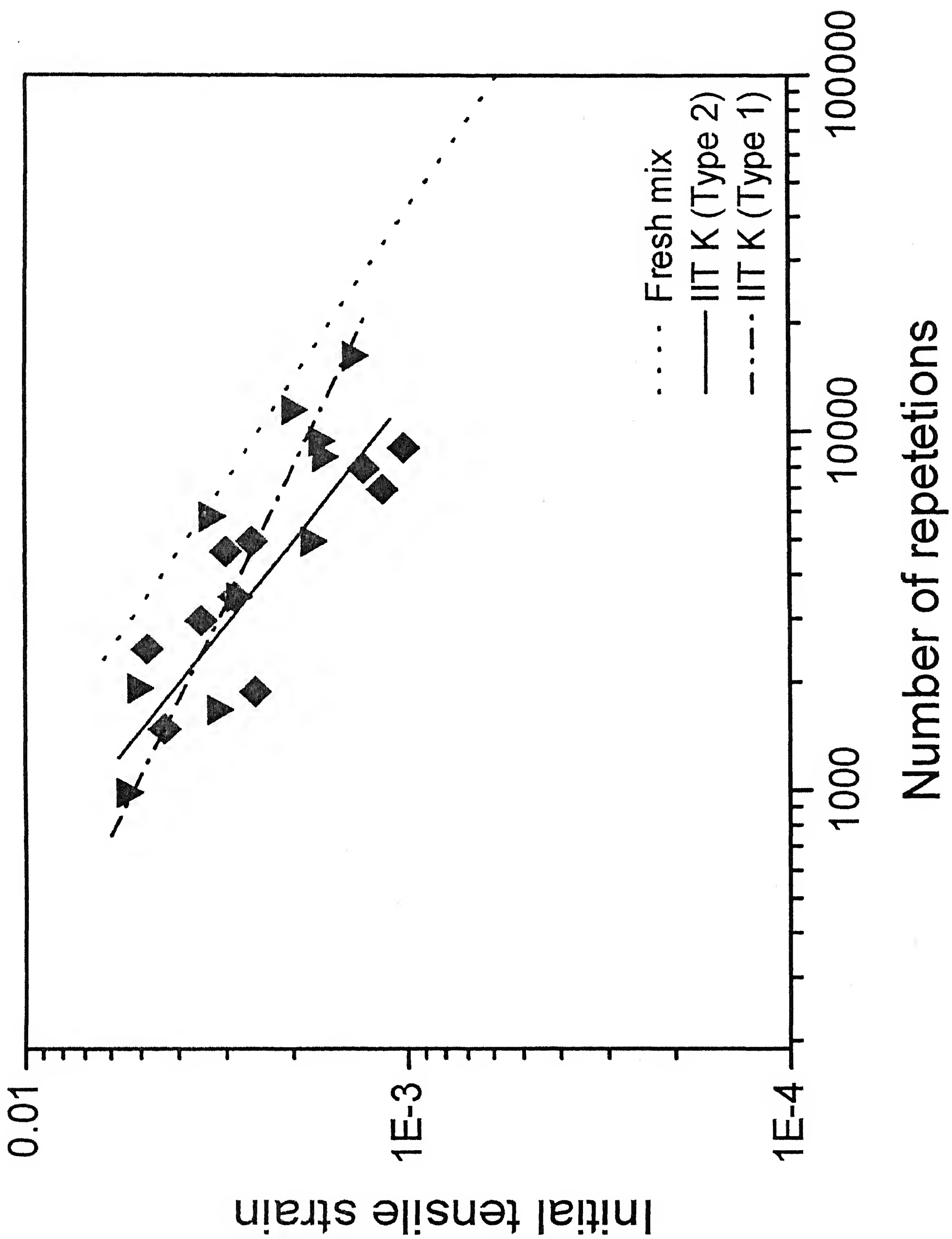

Figure 5.4: Comparison of fatigue performance of IIT K mixes with fresh mix

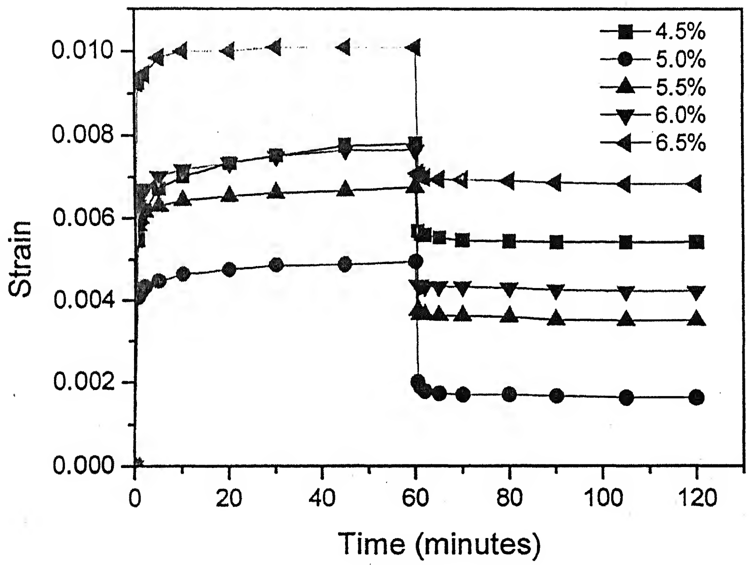

Figure 5.5: Variation of axial strain with time for fresh mix

5.4.2 Variation of permanent strain and recoverable strain

The variation of total strain, permanent strain and recoverable strain in different mixes at different bitumen contents have been studied. Figure 5.6 presents the variation permanent strain and recoverable strain with bitumen content in fresh mix.

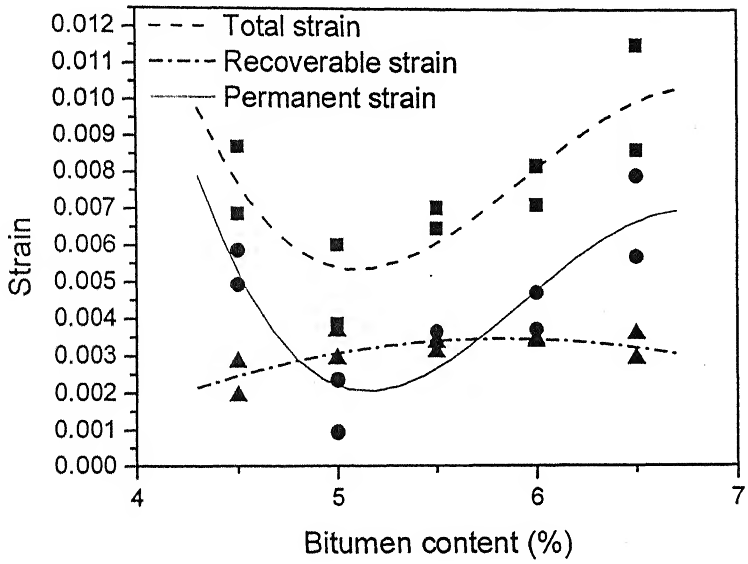

Figure 5.6: Variation of strain with bitumen content in fresh mix

5.4.3 Discussion

From Figure 5.6, it is clear that total strain and permanent strain is decreasing initially and then increases afterwards. At lower bitumen content, bonding between aggregates is less. Hence specimen undergoes more deformation. However at higher bitumen content, due to increased bitumen film thickness lubrication increases between aggregate interfaces. Hence due to slippery surface, total deformation and permanent deformation increases. Hence total strain and permanent strain is more at lower bitumen content and higher bitumen content. Somewhere in between, there exists a point, at which bitumen film thickness is just sufficient to impart more strength to sample. At

this point the permanent deformation will be least.

At lower bitumen content, binder being less, recovery of deformation is less. This is be due to realignment of aggregates particles. As bitumen content is increased the recoverable strain increases to a certain stage after which it again decreases. This is due to increased viscous component. Hence recoverable strain is having such a trend.

Figure 5.7 and 5.8 compares permanent strain and recoverable strain observed in different materials tested. Fresh mix has maximum recoverable strain. Hence it has better rutting resistance property. For all the cases maximum recoverable stress is observed to be in range of 5.5% to 6.5% of bitumen.

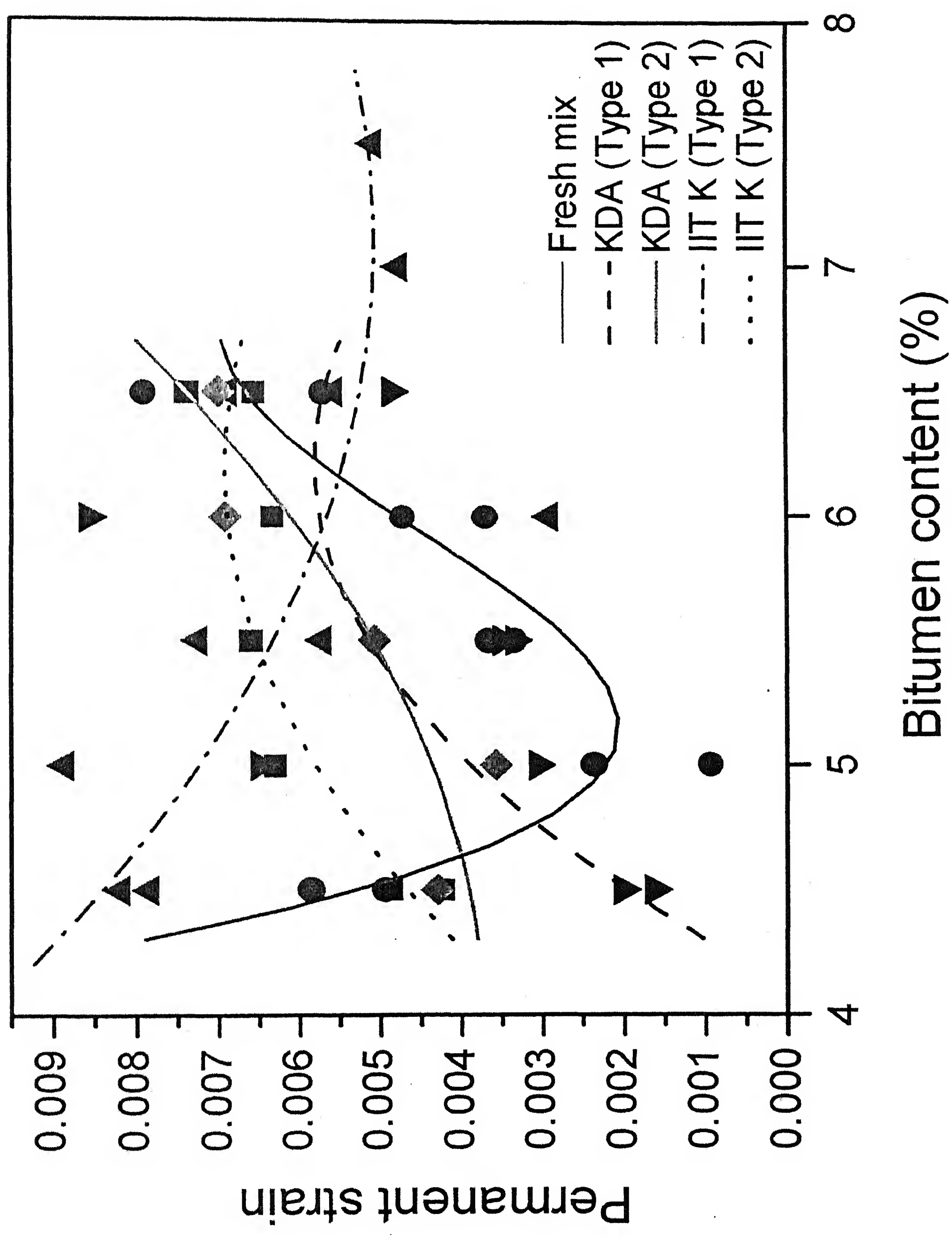

Figure 5.7: Comparison of permanent strain in different mixes

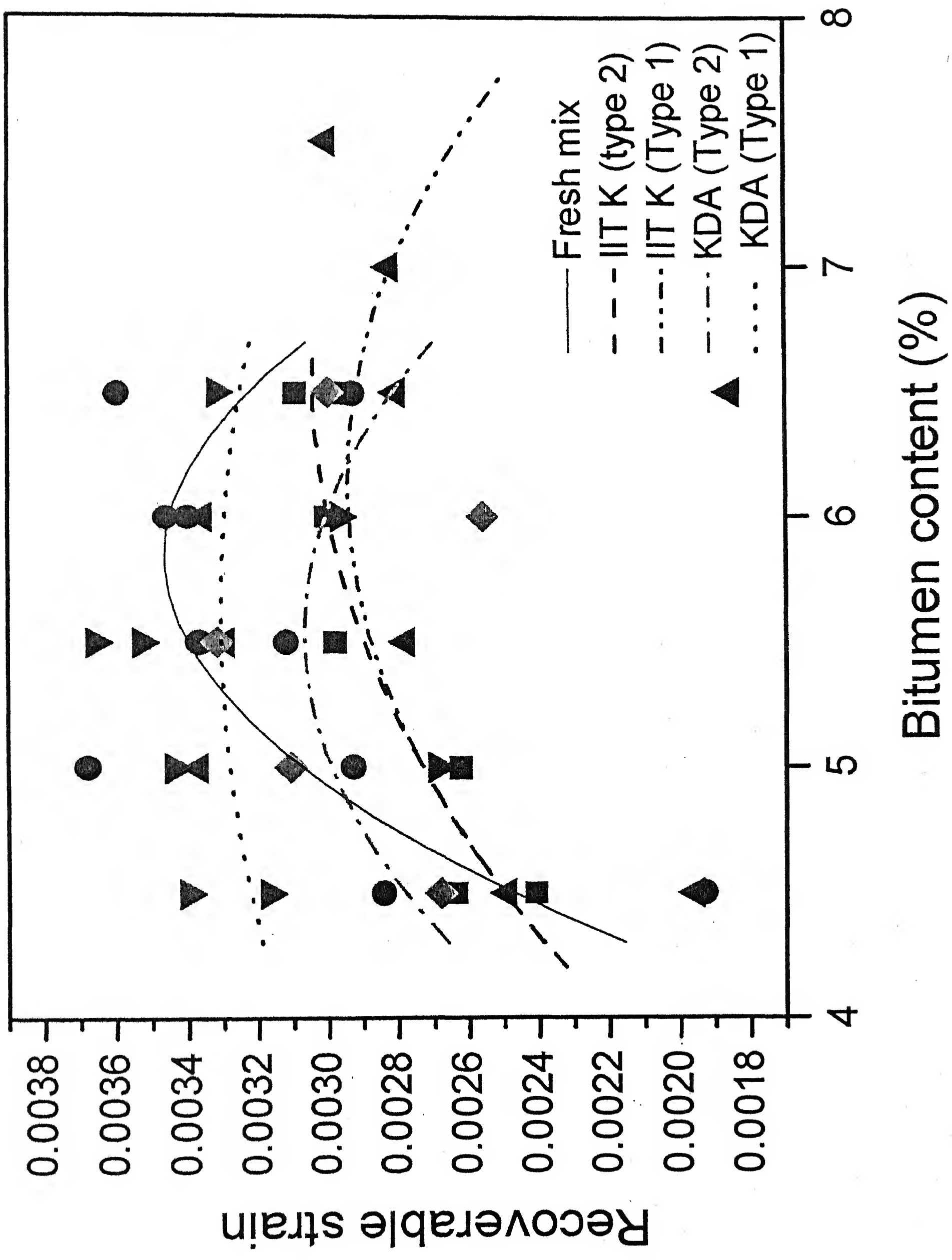

Figure 5.8: Comparison of recoverable strain in different mixes

Chapter 6

Conclusions and Further Scope

The conclusions of the present study can be summarized as follows.

- The various mix design techniques for hot central plant recycling has been reviewed. In most of the procedures, either quantity of RAP or fresh bitumen is fixed. The present approach attempted to propose a methodology where no such constraints are imposed. Proposed approach has been generalized for constituent estimation keeping in view the cost minimization or RAP quantity maximization using simple linear programming formulation.

- Fatigue tests were performed for the recycled mix and compared with the fresh mix. Since the temperatures among samples were different, the fatigue curve for the fresh mix was adjusted for the respective temperatures and compared. Comparison shows the fatigue performance of recycled mix is close to that of fresh mix.

- Creep tests indicated that permanent strain decreases initially and then starts increasing after a certain bitumen content. Also recoverable strain has maximum value at certain bitumen content. It is seen that creep behavior of recycled mix is comparable to the fresh mix.

6.1 Further Scope

This section gives some of the works that can be taken up as further study.

- As mentioned earlier rejuvinators are sometimes used for in recycling of bituminous pavements at some construction sites. Thus, the proposed formulation for mix proportioning can be suitably modified so as to incorporate rejuvenator in the mix design, and the performance of such mixes can be studied.
- Viscosity has been used to estimate binder mixing proportion. More rational parameter like complex shear modulus could be used to develop recommendations for binder mixing rule.
- The individual chemical composition of the asphalt affects its property. The ageing occurs because of the changes of the relative proportions of these constituents. Thus, adjustments in the chemical composition level can possibly work better towards recovery of property of aged asphalt, than just mixing bitumen with another bitumen. Suitable formation can be developed in this regard.

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Appendix A

Symbols Used

The following are the notations used in this thesis:

P = approximate total bitumen demand of recycled mix, percent by weight of mix

a = percent of mineral aggregate retained on 2.36mm sieve

b = percent of mineral aggregate passing on 2.36mm sieve and retained on 75μ sieve

c = percent of mineral aggregate passing 75μ sieve

K = .15 for 11 - 15 percent passing 75μ sieve,

= .18 for 6 - 10 percent passing 75μ sieve,

= .2 for 5 percent or less passing 75μ sieve.

F = 0 to 2.0 percent

η_t = target viscosity,

x_o = weight/volume fraction of aged bitumen,

η_o = viscosity of aged bitumen,

x_n = weight/volume fraction of fresh bitumen/ recycling agent.

η_n = viscosity of fresh bitumen/ recycling agent

P_b^R = Percentage of bitumen in recycled mix

P_b^{RAP} = Percentage of bitumen in old mix = OBC

P_{nb}^R = Percentage of fresh bitumen in recycled mix

P_{ob}^R = Percentage of old bitumen in recycled mix

P_{oa}^R = Percentage of old aggregates in recycled mix

P_{na}^R = Percentage of new aggregates in recycled mix

$P_{RAP}^R = (P_{ob}^R + P_{oa}^R)$= Percentage of RAP in recycled mix,

$(P_b^R)^l$ = Lower limit on Percentage of bitumen in recycled mix

$(P_b^R)^u$ = Upper limit on Percentage of bitumen in recycled mix

p_{ob} = proportion of old bitumen in mixture of old bitumen and fresh bitumen

p_{nb} = proportion of fresh bitumen in mixture of old bitumen and fresh bitumen

η_t^u = Upper limit on target viscosity

η_t^l = Lower limit on target viscosity

$\mathbf{P}^o$ = column matrix of old aggregate gradation

$\mathbf{p}_{oa}$ = proportion of old aggregates in mixture of old aggregates and new aggregates

$\mathbf{P}^n$ = column matrix of new aggregate gradation

$\mathbf{p}_{na}$ = proportion of new aggregates in mixture of old aggregates and new aggregates

$\mathbf{T}^l$ = column matrix representing lower limit on gradation requirements

$\mathbf{T}^u$ = column matrix representing lower limit on gradation requirements

$\mathbf{T}^m$ = column matrix representing mid point on gradation requirements

C_{RAP} = Cost of RAP per unit quantity

C_{na} = cost of new aggregate per unit quantity

C_{nb} = cost of fresh bitumen per unit quantity

N = Number of repetitions of load the beam can sustain before failure,

ϵ = Initial tensile strain,

E = Elastic modulus

E_0 = Elastic modulus at 0^0C

T = temperature

Appendix B

Fatigue Test Results

Fatigue test results using KDA (Type 1) material

Beam No	Test temperature (^{0}C)	Length (mm)	Breadth (mm)	Height (mm)	Weight (kg)	Unit Weight (kg/m^3)	Initial load (kg)	No of repetetions (N)	Deflection (mm)	Initial bending stress (Mpa)	Bending Strain	Initial stiffness (Mpa)
1	32	382	77.0	63.0	3.920	2115.39	273.516	3000	1.500	3.35	0.00304	1102.917
2	30	380	78.0	65.0	3.640	1889.34	254.653	6800	1.150	2.88	0.00243	1185.060
3	32	380	78.0	67.0	3.980	2004.15	278.232	700	2.500	2.96	0.00545	543.841
4	32	380	78.0	64.0	3.820	2013.75	254.653	1500	2.100	2.97	0.00437	679.860
5	32	380	76.0	61.0	3.850	2185.41	183.916	21200	0.550	2.42	0.00109	2222.174
6	30	380	76.0	65.0	3.920	2088.22	136.758	11200	0.780	1.59	0.00165	963.006
7	30	380	78.0	63.0	3.900	2088.55	254.653	12000	0.760	3.07	0.00156	1969.442
8	29	380	76.0	62.0	3.910	2183.67	254.653	10000	0.650	3.25	0.00131	2479.539
9	30	380	76.0	63.0	3.860	2121.53	231.074	22500	0.650	2.86	0.00133	2144.503

Fatigue test results using KDA (Type 2) material

Beam No	Test temperature (^{0}C)	Length (mm)	Breadth (mm)	Height (mm)	Weight (kg)	Unit Weight (kg/m^3)	Initial load (kg)	No of repetetions (N)	Deflection (mm)	Initial bending stress (Mpa)	Bending Strain	Initial stiffness (Mpa)
1	32	380	78.0	65.0	3.880	2013.91	348.97	1100	2.900	3.947	0.00613	643.989
2	28	380	78.0	62.5	3.840	2072.87	207.50	44700	0.070	2.539	0.00014	17844.289
3	32	380	77.5	70.0	4.160	2017.95	231.07	54700	0.295	2.268	0.00067	3377.983
4	31	380	76.0	64.0	3.720	2012.64	207.50	900	3.150	2.485	0.00656	379.025
5	30	380	77.0	65.0	3.870	2034.81	320.67	8000	0.800	3.675	0.00169	2173.038
6	31	380	77.0	65.0	3.790	1992.74	160.34	5500	1.650	1.837	0.00349	526.797
7	30	380	78.0	62.5	3.840	2072.87	297.10	22000	0.400	3.635	0.00081	4471.211
8	30	380	79.0	59.0	3.880	2190.63	254.65	3400	2.150	3.452	0.00412	836.857
9	31	380	78.0	66.0	3.980	2034.52	231.07	8800	1.300	2.535	0.00279	908.669
10	31	380	78.0	65.0	3.900	2024.29	165.05	13800	0.700	1.867	0.00148	1261.870

Fatigue test results using fresh aggregates

No	temperature (^{0}C)	Length (mm)	Breadth (mm)	Height (mm)	Weight (kg)	Weight (kg/m^3)	load (kg)	repetetions (N)	Deflection (mm)	stress (Mpa)	Bending	stiffness (Mpa)
1	30	380	76.0	61.0	3.650	2071.89	168.88	35600	0.750	2.23	0.00149	1496.368
2	30	380	76.0	60.0	3.690	2129.50	236.43	6000	1.900	3.22	0.00371	868.980
3	31	380	76.0	51.0	3.080	2091.14	260.56	14700	0.935	4.91	0.00155	3168.785
4	31	380	77.0	58.0	3.540	2085.94	188.18	17300	0.685	2.71	0.00129	2096.206
5	26	380	78.0	60.0	3.760	2114.26	183.92	8900	1.270	2.44	0.00248	985.353
6	27	380	78.0	62.0	3.940	2144.01	231.07	1900	2.440	2.87	0.00492	584.004
7	25	380	78.0	63.0	3.960	2120.69	254.65	3900	2.180	3.07	0.00447	686.594
8	26	380	76.0	68.0	4.200	2138.67	231.07	71500	0.250	2.45	0.00055	4433.993
9	28	380	78.0	64.0	4.050	2134.99	278.23	6900	1.500	3.25	0.00312	1039.933
10	24	380	78.0	60.0	4.050	2277.33	231.07	67800	0.200	3.07	0.00039	7861.347

Fatigue test results using IIT K (Type 1) material

Beam No	Test temperature (^{0}C)	Length (mm)	Breadth (mm)	Height (mm)	Weight (kg)	Unit Weight (kg/m^3)	Initial load (kg)	No of repetetions (N)	Deflection (mm)	Initial bending stress (Mpa)	Bending Strain	Initial stiffness (Mpa)
1	32	380	78	65.5	3.900	2008.84	141.47	9500	0.810	1.576	0.00173	913.476
2	34	380	77	64.0	3.910	2087.96	278.23	1950	2.470	3.289	0.00514	639.740
3	34	380	78	66.3	3.986	2028.36	113.18	3500	1.320	1.231	0.00285	432.396
4	34	380	78	64.0	3.961	2088.08	136.76	1000	2.645	1.596	0.00550	289.879
5	33	380	78	67.6	3.925	1958.91	160.34	5900	1.523	1.677	0.00335	501.033
6	32	380	78	61.5	3.620	1985.89	136.76	5000	0.905	1.728	0.00181	954.792
7	31	380	78	66.5	3.932	1994.87	136.76	11600	0.940	1.478	0.00203	727.093
8	32	380	78	56.0	3.168	1908.62	113.18	8600	0.925	1.725	0.00168	1023.977
9	32	380	78	60.0	3.219	1810.05	160.34	16300	0.720	2.129	0.00140	1515.226
10	33	380	78	59.3	3.366	1914.09	89.60	1700	1.660	1.217	0.00320	379.846

Fatigue test results using IIT K (Type 2) material

Beam No	Test temperature (^{0}C)	Length (mm)	Breadth (mm)	Height (mm)	Weight (kg)	Unit Weight (kg/m^3)	Initial load (kg)	No of repetetions (N)	Deflection (mm)	Initial bending stress (Mpa)	Bending Strain	Initial stiffness (Mpa)
1	34	380	78	65.0	3.783	1963.56	136.76	3000	1.660	1.5470	0.00351	440.894
2	33	380	77	67.0	3.855	1966.42	113.18	8000	0.600	1.2206	0.00131	933.736
3	34	380	78	65.6	3.865	1987.78	89.60	2500	2.265	0.9951	0.00483	205.948
4	33	380	78	64.0	3.845	2026.93	94.32	1500	2.095	1.1005	0.00436	252.401
5	34	380	78	65.7	3.834	1970.03	113.18	1900	1.185	1.2547	0.00253	495.878
6	34	380	78	67.0	3.826	1926.60	113.18	5000	1.185	1.2050	0.00258	466.716
7	33	380	78	64.0	3.824	2015.86	113.18	7000	0.560	1.3206	0.00117	1133.099
8	32	380	78	56.3	3.233	1936.37	113.18	9100	0.560	1.7047	0.00103	1661.838
9	32	380	78	58.0	3.496	2033.60	113.18	4700	1.605	1.6079	0.00303	531.174
10	32	380	78	55.0	3.244	1989.94	94.32	3500	1.605	1.4901	0.00287	519.101

Appendix C

Creep Test Results

Creep test results using fresh aggregates

Bitumen Content (%)	4.5	4.5	5	5	5.5	5.5	6	6	6.5	6.5
Height (mm)	64.75	62	64.75	60.5	65	69	64.75	63.5	62.5	62.5
Time (minutes)	strain at different time									
0	0	0	0	0	0	0	0	0	0	0
0.5	0.00556	0.00540	0.00309	0.00504	0.00585	0.00580	0.00579	0.00685	0.01048	0.00800
1	0.00587	0.00609	0.00324	0.00512	0.00592	0.00609	0.00602	0.00709	0.01072	0.00788
2	0.00602	0.00637	0.00332	0.00537	0.00600	0.00630	0.00618	0.00724	0.01088	0.00803
5	0.00633	0.00714	0.00340	0.00554	0.00608	0.00652	0.00649	0.00756	0.01120	0.00849
10	0.00649	0.00754	0.00355	0.00570	0.00615	0.00674	0.00664	0.00772	0.01136	0.00865
20	0.00664	0.00802	0.00363	0.00587	0.00623	0.00685	0.00680	0.00787	0.01136	0.00865
30	0.00672	0.00831	0.00371	0.00599	0.00631	0.00692	0.00695	0.00803	0.01152	0.00865
45	0.00680	0.00871	0.00371	0.00603	0.00631	0.00703	0.00710	0.00819	0.01152	0.00865
60	0.00687	0.00871	0.00386	0.00603	0.00646	0.00703	0.00710	0.00819	0.01152	0.00865
60.5	0.00525	0.00613	0.00139	0.00264	0.00369	0.00380	0.00386	0.00488	0.00816	0.00602
61	0.00510	0.00609	0.00124	0.00252	0.00354	0.00377	0.00386	0.00488	0.00816	0.00587
62	0.00510	0.00607	0.00108	0.00248	0.00354	0.00375	0.00382	0.00484	0.00808	0.00587
65	0.00502	0.00601	0.00104	0.00242	0.00350	0.00375	0.00382	0.00484	0.00800	0.00587
70	0.00494	0.00597	0.00100	0.00242	0.00350	0.00373	0.00382	0.00484	0.00800	0.00587
80	0.00494	0.00593	0.00100	0.00240	0.00346	0.00373	0.00378	0.00480	0.00800	0.00579
90	0.00494	0.00589	0.00097	0.00238	0.00338	0.00366	0.00375	0.00476	0.00792	0.00579
105	0.00494	0.00587	0.00093	0.00236	0.00335	0.00366	0.00371	0.00472	0.00792	0.00571
120	0.00494	0.00587	0.00093	0.00236	0.00335	0.00366	0.00371	0.00472	0.00792	0.00571

Creep test results using KDA (Type 1) material

Bitumen Content (%)	4.5	4.5	5	5	5.5	5.5	6	6.5	6.5
Height (mm)	65	64.75	65	65	63.5	64.75	66	65	64.75
Time (minutes)	strain at different time								
0	0	0	0	0	0	0	0	0	0
0.5	0.00392	0.00402	0.00608	0.00492	0.00386	0.00440	0.00795	0.00408	0.00687
1	0.00415	0.00421	0.00646	0.00519	0.00413	0.00479	0.00864	0.00427	0.00703
2	0.00425	0.00440	0.00715	0.00546	0.00433	0.00533	0.00938	0.00450	0.00710
5	0.00442	0.00463	0.00788	0.00577	0.00512	0.00587	0.01008	0.00481	0.00749
10	0.00458	0.00490	0.00829	0.00608	0.00555	0.00614	0.01057	0.00494	0.00764
20	0.00465	0.00508	0.00879	0.00623	0.00606	0.00649	0.01102	0.00519	0.00799
30	0.00477	0.00514	0.00902	0.00635	0.00646	0.00668	0.01125	0.00531	0.00811
45	0.00479	0.00537	0.00917	0.00642	0.00669	0.00687	0.01148	0.00546	0.00813
60	0.00481	0.00541	0.00919	0.00650	0.00717	0.00687	0.01155	0.00558	0.00817
60.5	0.00188	0.00232	0.00673	0.00338	0.00378	0.00355	0.00886	0.00223	0.00548
61	0.00179	0.00220	0.00663	0.00333	0.00368	0.00353	0.00871	0.00215	0.00500
62	0.00177	0.00218	0.00660	0.00329	0.00364	0.00346	0.00871	0.00212	0.00492
65	0.00173	0.00212	0.00656	0.00323	0.00360	0.00340	0.00867	0.00210	0.00490
70	0.00169	0.00207	0.00652	0.00315	0.00358	0.00338	0.00864	0.00204	0.00488
80	0.00167	0.00201	0.00650	0.00312	0.00358	0.00336	0.00862	0.00204	0.00488
90	0.00165	0.00201	0.00650	0.00312	0.00356	0.00334	0.00862	0.00202	0.00485
105	0.00163	0.00201	0.00650	0.00306	0.00350	0.00334	0.00858	0.00200	0.00485
120	0.00163	0.00201	0.00650	0.00306	0.00350	0.00334	0.00858	0.00200	0.00485

Creep test results using KDA (Type 2) material

Bitumen Content (%)	4.5	5	5.5	6	6.5	6.5
Height (mm)	66.25	64.75	65.6	66.5	65.5	64.75
Time (minutes)	strain at different time					
0	0	0	0	0	0	0
0.5	0.00475	0.00517	0.00572	0.00707	0.00702	0.00486
1	0.00506	0.00544	0.00633	0.00759	0.00740	0.00517
2	0.00540	0.00571	0.00716	0.00805	0.00809	0.00552
5	0.00581	0.00610	0.00770	0.00861	0.00865	0.00595
10	0.00604	0.00633	0.00777	0.00898	0.00897	0.00618
20	0.00638	0.00649	0.00816	0.00929	0.00927	0.00653
30	0.00664	0.00656	0.00827	0.00936	0.00939	0.00680
45	0.00698	0.00660	0.00838	0.00947	0.00992	0.00714
60	0.00698	0.00668	0.00838	0.00947	0.01000	0.00714
60.5	0.00460	0.00378	0.00541	0.00707	0.00557	0.00471
61	0.00445	0.00375	0.00537	0.00703	0.00708	0.00456
62	0.00442	0.00369	0.00530	0.00695	0.00704	0.00452
65	0.00440	0.00367	0.00530	0.00695	0.00700	0.00450
70	0.00436	0.00365	0.00518	0.00695	0.00700	0.00446
80	0.00430	0.00363	0.00514	0.00695	0.00700	0.00440
90	0.00430	0.00357	0.00507	0.00692	0.00700	0.00440
105	0.00430	0.00357	0.00507	0.00692	0.00700	0.00440
120	0.00430	0.00357	0.00507	0.00692	0.00700	0.00440

Creep test results using IIT K (Type 1) material

Bitumen Content (%)	4.5	4.5	5.0	5.5	5.5	6.0	6.5	6.5	7.0	7.5
Height (mm)	69	67.25	68.25	64.5	64.75	67	62	61.5	62	65
Time (minutes)	strain at different time									
0	0	0	0	0	0	0	0	0	0	0
0.5	0.00348	0.00796	0.00857	0.00775	0.00687	0.00403	0.00565	0.00707	0.00532	0.00654
1	0.00478	0.00818	0.00894	0.00837	0.00710	0.00425	0.00597	0.00748	0.00565	0.00677
2	0.00594	0.00900	0.00945	0.00876	0.00741	0.00455	0.00629	0.00797	0.00597	0.00700
5	0.00739	0.00937	0.01026	0.00930	0.00776	0.00515	0.00661	0.00854	0.00645	0.00746
10	0.00855	0.00974	0.01084	0.00961	0.00822	0.00534	0.00694	0.00894	0.00677	0.00777
20	0.00913	0.00996	0.01136	0.01008	0.00838	0.00560	0.00702	0.00931	0.00710	0.00788
30	0.00957	0.01011	0.01194	0.01023	0.00846	0.00582	0.00718	0.00945	0.00726	0.00800
45	0.01000	0.01019	0.01223	0.01054	0.00849	0.00604	0.00742	0.00957	0.00742	0.00808
60	0.01014	0.01033	0.01223	0.01054	0.00849	0.00627	0.00742	0.00967	0.00758	0.00808
60.5	0.00841	0.00796	0.00908	0.00736	0.00587	0.00313	0.00573	0.00699	0.00484	0.00531
61	0.00826	0.00796	0.00901	0.00736	0.00579	0.00310	0.00573	0.00699	0.00484	0.00527
62	0.00826	0.00794	0.00901	0.00733	0.00573	0.00310	0.00573	0.00697	0.00484	0.00525
65	0.00822	0.00790	0.00897	0.00729	0.00573	0.00304	0.00567	0.00693	0.00480	0.00523
70	0.00819	0.00786	0.00890	0.00725	0.00571	0.00300	0.00560	0.00689	0.00476	0.00512
80	0.00819	0.00784	0.00886	0.00725	0.00571	0.00291	0.00560	0.00689	0.00476	0.00510
90	0.00819	0.00784	0.00886	0.00725	0.00571	0.00291	0.00558	0.00687	0.00472	0.00508
105	0.00819	0.00784	0.00886	0.00725	0.00571	0.00291	0.00556	0.00687	0.00476	0.00508
120	0.00819	0.00784	0.00886	0.00725	0.00571	0.00291	0.00556	0.00687	0.00476	0.00508

Creep test results using IIT K (Type 2) material

Bitumen Content (%)	4.5	4.5	5.0	5.5	5.5	6.0	6.5	6.5
Height (mm)	66	67.5	67.25	63.5	66.25	63.25	63	59
Time (minutes)	strain at different time							
0	0	0	0	0	0	0	0	0
0.5	0.00591	0.00504	0.00706	0.00372	0.00777	0.00569	0.00794	0.00831
1	0.00617	0.00530	0.00743	0.00388	0.00838	0.00648	0.00849	0.00862
2	0.00648	0.00563	0.00781	0.00419	0.00868	0.00696	0.00885	0.00886
5	0.00682	0.00607	0.00818	0.00450	0.00898	0.00767	0.00952	0.00928
10	0.00712	0.00641	0.00848	0.00473	0.00921	0.00822	0.00976	0.00941
20	0.00727	0.00650	0.00870	0.00473	0.00951	0.00854	0.00998	0.00953
30	0.00735	0.00657	0.00879	0.00484	0.00951	0.00885	0.01008	0.00960
45	0.00750	0.00663	0.00881	0.00488	0.00955	0.00917	0.01020	0.00964
60	0.00750	0.00663	0.00892	0.00492	0.00958	0.00933	0.01036	0.00966
60.5	0.00515	0.00444	0.00656	0.00240	0.00679	0.00632	0.00754	0.00665
61	0.00508	0.00441	0.00652	0.00238	0.00675	0.00632	0.00750	0.00665
62	0.00506	0.00433	0.00649	0.00234	0.00672	0.00632	0.00750	0.00663
65	0.00502	0.00431	0.00647	0.00231	0.00672	0.00632	0.00742	0.00663
70	0.00494	0.00430	0.00643	0.00227	0.00660	0.00632	0.00742	0.00663
80	0.00489	0.00426	0.00639	0.00223	0.00660	0.00632	0.00742	0.00661
90	0.00489	0.00424	0.00639	0.00223	0.00660	0.00632	0.00742	0.00661
105	0.00487	0.00422	0.00639	0.00223	0.00660	0.00632	0.00738	0.00657
120	0.00487	0.00422	0.00630	0.00223	0.00660	0.00632	0.00738	0.00657